

This Page Is Inserted by IFW Operations
and is not a part of the Official Record

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images may include (but are not limited to):

- BLACK BORDERS
- TEXT CUT OFF AT TOP, BOTTOM OR SIDES
- FADED TEXT
- ILLEGIBLE TEXT
- SKEWED/SLANTED IMAGES
- COLORED PHOTOS
- BLACK OR VERY BLACK AND WHITE DARK PHOTOS
- GRAY SCALE DOCUMENTS

IMAGES ARE BEST AVAILABLE COPY.

**As rescanning documents *will not* correct images,
please do not report the images to the
Image Problem Mailbox.**

XR 3,911,733

1 X 50-51 Y

United St^a

Bhuta et al.

X 3046 C

X 356/109

[11] 3,911,733

[45] Oct. 14, 1975

(4)

[54] OPTICAL SIGNATURE METHOD AND APPARATUS FOR STRUCTURAL INTEGRITY VERIFICATION

[75] Inventors: Pravin G. Bhuta; David A. Evensen, both of Torrance; Edmund K. Burchman, Los Alamitos, all of Calif.

[73] Assignee: TRW Inc., Redondo Beach, Calif.

[22] Filed: Apr. 1, 1974

[21] Appl. No.: 456,998

[52] U.S. Cl..... 73/88 A; 73/67.3; 73/91

[51] Int. Cl.²..... G01N 3/32

[58] Field of Search 73/88 A, 91, 67.3, 100; 356/71

*Primary Examiner—Jerry W. Myracle
Attorney, Agent, or Firm—Daniel T. Anderson;
Donald R. Nyhagen; Edwin A. Oser*

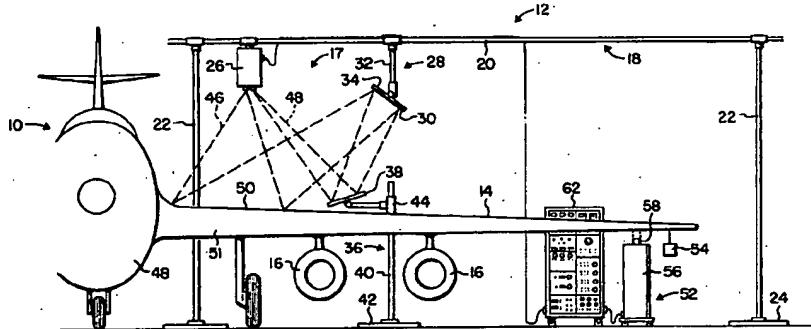
[57] ABSTRACT

The structural integrity of a load bearing structure is periodically evaluated by recording on the same holographic recording medium two successive holograms of the structure while the latter is in two different stress conditions, respectively, to produce a holographic interferogram which may be reconstructed to create a deformation fringe pattern representing the deformations in the structure resulting from the change in the stress conditions. This deformation pattern is compared with an earlier deformation pattern of the structure resulting from the same stress conditions to determine differences, if any, between the two patterns, such differences being indicative of a reduction in the stiffness and hence structural integrity of the structure due to weakening of the latter by fatigue damage, stress corrosion cracking, and/or other causes.

22 Claims, 6 Drawing Figures

[56] References Cited
UNITED STATES PATENTS

3,136,154 6/1964 Christansen..... 73/91 UX
3,631,713 1/1972 Marom 73/67.3



3911733
OR IN 73/88A

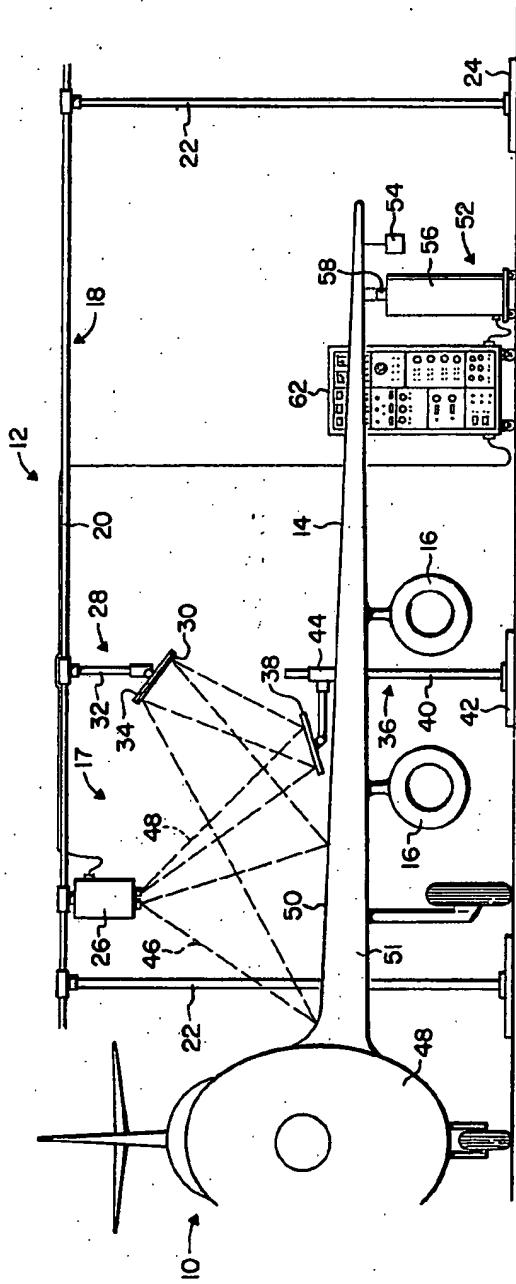


Fig. 1

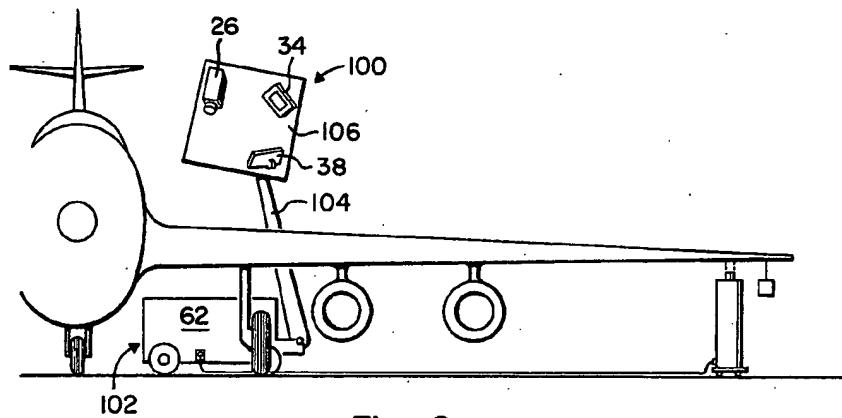


Fig. 2

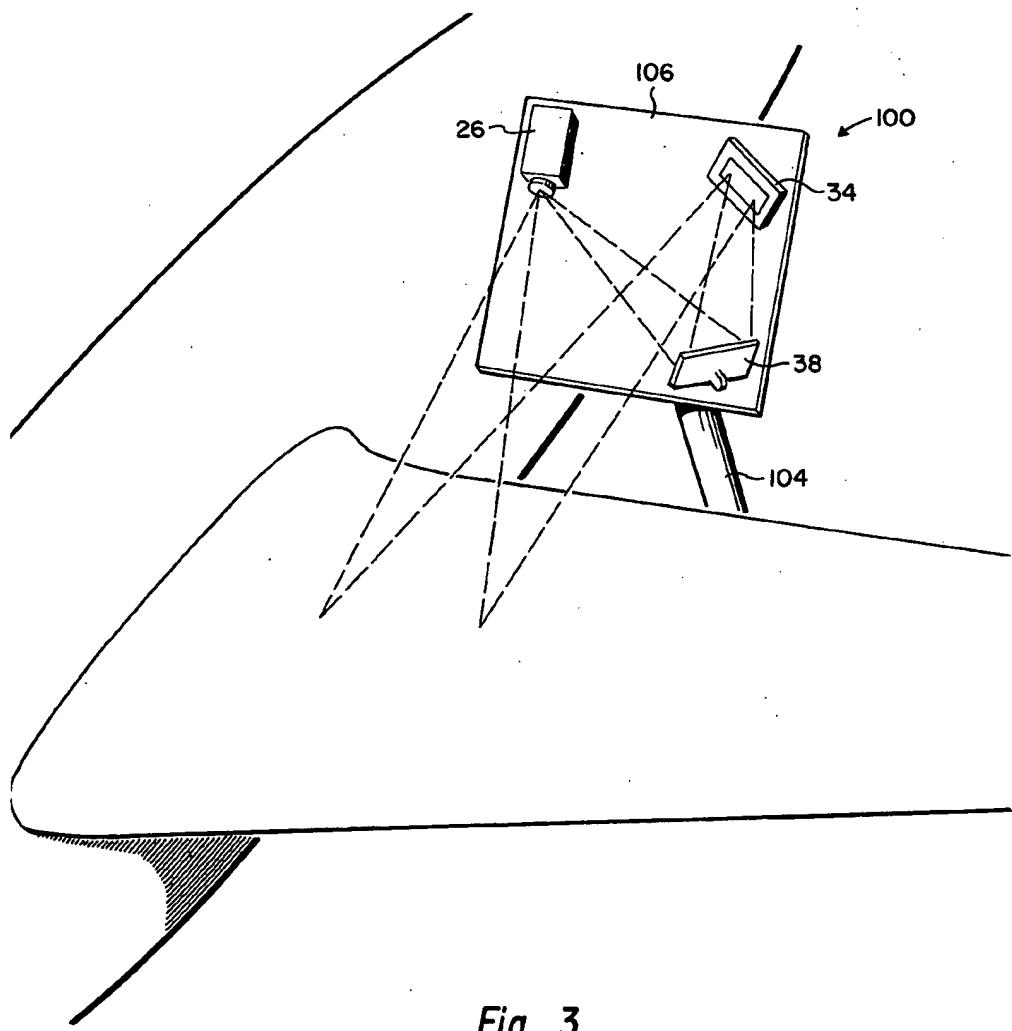


Fig. 3

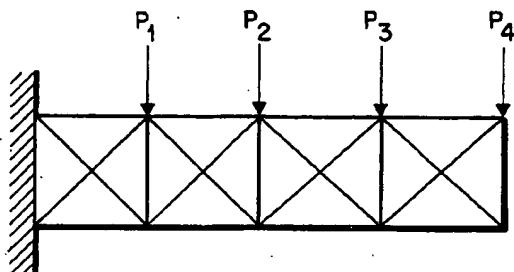


Fig. 1A

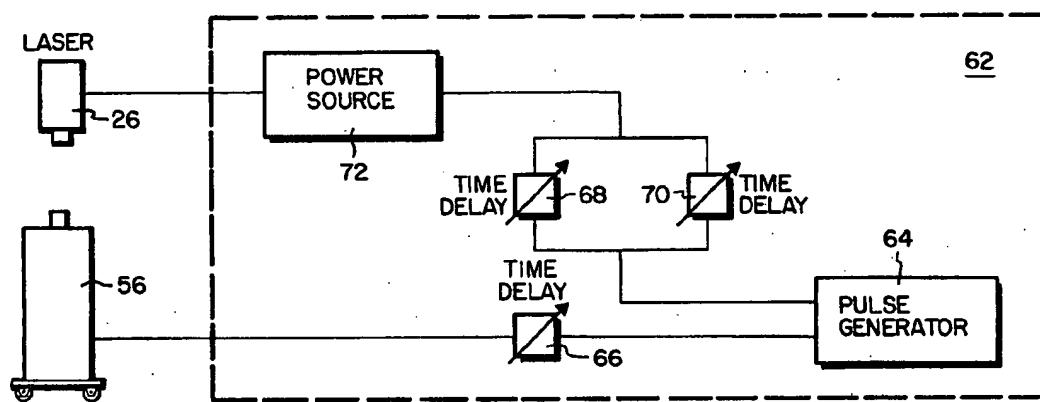


Fig. 1B

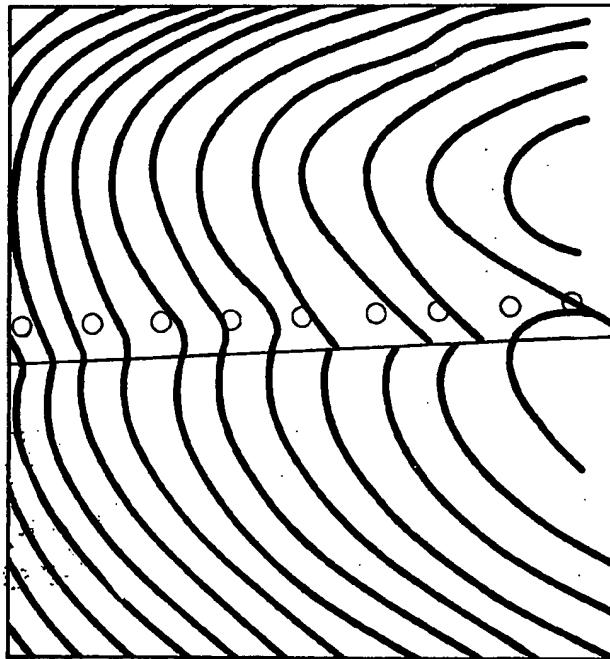


Fig. 4

**OPTICAL SIGNATURE METHOD AND
APPARATUS FOR STRUCTURAL INTEGRITY
VERIFICATION**

BACKGROUND OF THE INVENTION

1. Field of the Invention:

This invention relates generally to the art of nondestructive inspection and more particularly to a novel nondestructive inspection method and apparatus utilizing holographic interferometry for evaluating the structural integrity of load bearing structures.

2. Prior Art:

As will become readily apparent from the ensuing description, the nondestructive inspection technique of this invention may be utilized to evaluate the structural integrity of virtually any structure. The invention is particularly useful for evaluating the integrity of redundant load bearing structures, however, that is load bearing structures having multiple load paths. For this reason, the invention will be described in connection with its application to evaluating the structural integrity of such a redundant load bearing structure, specifically an aircraft wing structure. In view of the above noted broader utility of the invention, it will be understood, of course, that the described application involving aircraft wing inspection is purely illustrative and not limiting in nature.

An aircraft wing is a highly redundant load bearing structure having multiple internal load bearing members providing multiple load paths through the structure. The wing structure is designed to sustain loads substantially in excess of those which are encountered in normal aircraft service. Over a period of time, however, a wing structure is prone to loss of its structural integrity, that is weakening of its load bearing members due to fatigue damage, stress corrosion cracking, and other causes. Fatigue damage, of course, involves cracking of the wing load bearing members, loosening of joints and rivets, and other weakening of the wing structure caused by the frequent load reversals which occur in the structure during flight, landing, and take-off. Stress corrosion cracking occurs in aircraft which operate in an ocean environment and is caused by the corrosive action of salt water. In order to assure continued safe aircraft operation, therefore, it is necessary to periodically evaluate the structural integrity of aircraft wings, as well as other parts of the aircraft, of course.

A variety of inspection and testing techniques have been devised to evaluate the structural integrity of aircraft wings and other aircraft parts. One common inspection technique, for example, involves installing accelerometers on selected structural members for counting stress reversals experienced by the members. From these counts and a statistical model based on the behavior of the particular aircraft structure of interest and statistical considerations regarding the distribution and size of defects, fatigue damage may be predicted. At appropriate times, the wing structure may be disassembled and subjected to actual fatigue inspection using x-rays or other nondestructive inspection techniques and/or fatigue damage tests. This method of evaluating structural integrity, however, is extremely costly and time consuming. The same applies to the current methods of inspecting aircraft wings and other structures for stress corrosion cracks, which methods require stripping all paint from the surfaces to be inspected, inspection of the surfaces by ultrasonic or

other inspection techniques, and repainting of the surfaces. Accordingly, there is a need for an improved nondestructive inspection technique for evaluating the structural integrity of load bearing structures, particularly highly redundant load bearing structures, such as aircraft wings and other aircraft structures and parts.

SUMMARY OF THE INVENTION

This invention provides such an improved inspection technique, involving holographic interferometry. The improved inspection technique is based on the fact that any loss of structural integrity, that is weakening, of a load bearing structure due to fatigue damage, stress corrosion cracking, or other causes reduces the effective stiffness of the structure. This reduction in stiffness, in turn, changes the distortions which the structure will experience in response to any given loading or stressing of the structure. The present inspection technique utilizes holographic interferometry to detect such changes in distortion and thereby changes in the structural integrity of the test structure.

According to the invention, a load bearing structure is periodically inspected by establishing in the structure two successive predetermined stress conditions of differing magnitude and recording on the same holographic recording medium a first hologram of the structure while the latter is in one stress condition and a second hologram of the structure while the latter is in the other stress condition. The resulting hologram recorded on the recording medium is an interferogram which may be holographically constructed to produce a deformation fringe pattern whose fringe lines depict or represent the deformations occurring in the structure due to the change from one stress condition to the other. This deformation pattern is compared to an earlier deformation pattern of the structure produced with the same stress conditions to determine any differences in the patterns. Differences, if any, between the patterns are indicative of a change in the structural integrity of the structure in the interval between recording of the two interferograms.

The two stress conditions required for each periodic inspection of the structure may be established by either or both static or dynamic loading of the structure. According to the static loading procedure, the structure to be inspected is subjected to a given static load, which may be simply the weight of the structure or an additional static load, during recording of the first hologram. The static load on the structure is then changed and the second hologram is recorded. According to the dynamic loading procedure, an impact or impulsive load is applied to the structure to effect propagation of stress waves through the structure. These stress waves establish a first stress in the structure when the first hologram is recorded and a second stress condition when the second hologram is recorded. According to the combined static and dynamic loading procedure, the structure is subjected to a constant static load in addition to the impulsive load.

As noted earlier, the invention will be described in connection with its application to aircraft wing inspection. In this particular application, the wings of an aircraft are inspected at regular intervals and the aircraft is placed into normal flight service after each inspection, such that the wings are subjected to flight, landing, and takeoff loads and stresses in the periods between inspections. Accordingly, a series of deformation

patterns of the wings are generated which permit effective monitoring of the structural integrity of the wings. The loads exerted on the wings for inspection purposes are related to their normal flight loading. A primary advantage of the invention in this application resides in the ability to evaluate the wing integrity without disassembly of the wings or removal of paint from the wing surfaces. The invention also provides a portable holographic inspection apparatus for practicing the inspection technique of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates inspection apparatus according to the invention set up for inspecting the root section of an aircraft wing;

FIG. 1A is a simplified load diagram of the wing;

FIG. 1B is an electrical circuit diagram of the wing;

FIG. 2 illustrates a modified inspection apparatus set up for inspecting an aircraft wing root section;

FIG. 3 is an enlarged fragmentary perspective view of the structure in FIG. 2; and

FIG. 4 illustrates a simple deformation pattern produced by the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring first to FIG. 1, there is illustrated an airplane 10 and inspection apparatus 12 according to the invention for periodically evaluating the structural integrity of the airplane wing 14. Attached to the underside of the wing are engines 16. Before describing the inspection apparatus 12, it is well to consider the structural and deformation characteristics of such a wing.

The simplest structural model for the wing is a cantilever beam, but such a model is clearly inadequate for understanding fatigue of the wing. In reality, the wing is a complex, redundant structure, with multiple load paths. A simplified example of such a redundant structure is sketched in FIG. 1A.

The deflection of such a redundant structure can be computed from the matrix equation

$$[K] \vec{u} = \vec{P}$$

(1)

where \vec{P} is the load vector, \vec{u} the displacement vector, and K is the stiffness matrix, which depends upon the stiffness of the individual members, i.e., the members of the truss (or wing) have individual area A_i , length l_i , modulus E_i , etc., which contribute to the individual stiffnesses and influence the matrix elements $[k_{ij}]$.

When the structure is "brand-new," the original stiffness matrix is $[K_o]$, and a set of loads \vec{P} produces a certain deflection pattern characterized by \vec{u}_o .

$$[K_o] \vec{u}_o = \vec{P}$$

$$\vec{u}_o = [K_o]^{-1} \vec{P}$$

(2)

Now suppose the wing structure is subjected to many loading cycles, and fatigue cracks begin to develop in one or more of the wing load carrying members. One effect of these fatigue cracks is to change the effective stiffness of the load-carrying members. For example, the effective cross-sectional area A_i of the fatigued members might decrease. In this case, the individual stiffness of the members will change to $(k_{ij} + \delta k_{ij})$ where δk_{ij} is the change in stiffness. Then the stiffness matrix becomes

$$[K'] = [K_o] + [\delta K]$$

(3)

for the "used" structure and Equation (1) then becomes

$$[K'] \vec{u} = \vec{P} = \{[K_o] + [\delta K]\} \vec{u} = \vec{P}$$

(4)

which can be solved for the deflection

$$\vec{u} = \vec{u}_o + \delta \vec{u}$$

(5)

where $\delta \vec{u}$ is the change in the displacement or distortion vector (which results from the change in stiffness δK due to fatigue effects).

The basic aim of the present nondestructive inspection method is to detect this change $\delta \vec{u}$ in displacement or distortion. Since holographic interferometry is very sensitive to small changes in displacement, it is an ideal tool to use for detection $\delta \vec{u}$.

For example, assume a brand new wing structure is loaded by a static load vector, \vec{P}_o , which produces a displacement \vec{u}_o , and that a first hologram of the wing is recorded on a holographic recording medium while under such load. Assume further that the wing load is changed by an amount ΔP , and a second hologram of the wing is recorded on the same recording medium. The resulting double-exposed medium or hologram constitutes an interferogram which contains or records holographic information representing the incremental wing distortion or displacement Δu produced by the load change ΔP . This incremental displacement may be termed the displacement signature of the wing at the load \vec{P}_o . This signature may be observed by holographically reconstructing the interferogram to produce a holographic image of the wing containing fringe lines representing the incremental displacements or distortions Δu produced in the wing by the load change ΔP . In the present description, this holographic image is referred to as a deformation fringe pattern or simply a deformation pattern.

Assume now that the aircraft is placed in service for a period of time, such that the aircraft wing experiences many stress cycles, i.e., stress or load reversals, and that the stiffness of the wing changes because of fatigue cracking and/or other causes. Assume further that following such service period the aircraft is brought in for inspection, loaded to the same static load, \vec{P}_o , and then its response $\Delta u'$ to the same load increment ΔP , is again recorded with double-exposure holography. Now, since the structural stiffness of the wing has changed due to fatigue, its "signature" $\Delta u'$ is not identical with the original signature Δu . The difference in signature (mathematically $\Delta u' - \Delta u$) can be used as a measure of the change in stiffness ($K_o + \delta K$) and is related to fatigue damage in the structure.

The signature difference $\Delta u' - \Delta u$ can be observed by holographically reconstructing the second double-exposed hologram or interferogram to produce a second deformation pattern of the wing and comparing the latter pattern with the first deformation pattern of the wing. Any difference between these patterns, that is any difference between the number, shape, width, and/or spacing of their fringe lines, is indicative of a change in the wing signature, i.e., incremental displacement produced by the load change ΔP , and hence of a change in the wing stiffness. A change in the wing stiff-

ness, in turn, indicates that the wing has been weakened by fatigue damage or other causes.

The foregoing discussion effectively summarizes one nondestructive inspection technique according to this invention for evaluating the structural integrity of an aircraft wing. As noted earlier, of course, and as will be evident from the discussion, the same technique may be used to evaluate the structural integrity of virtually any structure.

It will be apparent to those versed in the art that the above technique suffers from one disadvantage. This disadvantage, which may not exist in all applications of the invention, resides in the fact that the test structure and holography apparatus must remain absolutely stationary during the recording of each double-exposed hologram or interferogram for reasons which are obvious to those familiar with holography.

An alternative and preferred inspection procedure, which avoids the foregoing disadvantage, involves dynamic or both static and dynamic loading of the test structure. This dynamic loading inspection technique is explained below. Suffice it to say at this point that the dynamic technique, while fundamentally equivalent to the static loading technique and yielding essentially the same deformation patterns as the static technique, permits the use of pulsed laser holography to produce the inspection interferograms and thereby avoids the above noted disadvantage of the static technique.

Moreover, when the load-deflection curve of the test structure is nonlinear, the dynamic inspection technique will give a measure of the "incremental" stiffness matrix

$$[K_i] = (\Delta P) (\Delta u)^{-1}$$

which is load-dependent. From a practical standpoint, the application of a static load related to the normal service load of the test structure in addition to the dynamic load on the structure will serve to open up fatigue cracks, etc., and thereby yield a more accurate evaluation of the actual stiffness of the structure at the operating load point.

The preferred dynamic load inspection technique of the invention will now be explained by reference to FIG. 1. The inspection apparatus 12 illustrated in the figure is designed to record the successive interferograms of the aircraft wing 14 from which are reconstructed the deformation patterns for evaluating the structural integrity of the wing, or more correctly detecting any changes in the wing stiffness over a period of time.

The illustrated inspection apparatus 12 comprises a pulsed laser holographic apparatus 17 including a supporting frame 18, which is preferably portable. The particular support frame shown has a horizontal rail 20 supported at its ends on standards 22 with enlarged bases 24 for resting on the floor. It will be understood that the support frame 18 will be constructed and arranged to be sufficiently rigid and stable to enable operation of the apparatus in the manner explained later.

Slidably supported on the rail 20, for adjustment along and rotation about the rail, are a laser 26 and a holder 28 for a holographic recording plate 30. The plate holder 28 comprises a hanger 32 slidably mounted at its upper end on the rail 20. Swivelled on the lower end of the hanger is an adjustable support 34 for the holographic plate 30.

The holographic apparatus 17 also includes a support 36 for a mirror 38. Mirror support 36 comprises a standard 40 with a large base 42 for resting on the floor. Vertically adjustable along the standard 40 is a horizontal bracket 44. Mirror 38 is swivelled on the outer end of the bracket for adjustment of the mirror relative to the mirror support.

Laser 26 is a pulsed laser, such as a pulsed ruby laser, including optics (now shown) for splitting the laser beam into a divergent coherent scene beam 46 and a divergent coherent reference beam 48. The laser optics are arranged to project these beams along divergent paths, as shown, and may be adjustable to change the beam directions.

Holographic apparatus 17 is positioned in accordance with the particular structural area to be inspected. In FIG. 1, for example, the area to be inspected is the upper surface area 50 of the wing root region 51. The apparatus 17 is set up along the trailing edge of the wing with the support frame 18 extending lengthwise of the wing and the left-hand frame standard positioned close to the aircraft fuselage 48. The laser 26 is placed at the left end of the frame rail 26 and adjusted so that its scene beam 46 illuminates the wing root surface area 50. The holographic plate 30 is placed to receive from the surface coherent light of the scene beam. The mirror 38 is positioned in the path of the reference beam 48 and adjusted to reflect this beam to the plate 30. It will be understood, of course, that the laser, holographic plate, and mirror are located to attain the proper path lengths of the scene and reference beams. Accordingly, each time the laser 26 is pulsed, a hologram of the wing surface area 50 is recorded on the holographic recording plate.

In addition to the holographic apparatus 17, the inspection apparatus 12 includes means 52 for both statically and dynamically loading or stressing the wing 14. Wing loading means 52 comprises a weight 54 which is suspended from the wing tip for exerting a static load on the wing and an impulsive loading device 56 for applying an impulse to the wing. The weight 54 is selected to exert a static load which is an arbitrary fraction of the normal static load on the wing in flight. The impulsive loading device 56 has a plunger 58 and electrically actuated means for driving the plunger into impact with the wing 14 to apply an impulse to the wing. This means may be a solenoid, a pneumatic actuator controlled by a solenoid valve, or other suitable electrically actuated means. Each such impulse causes stress waves to propagate along the wing.

The impulsive loading device 56 may be supported in any convenient way relative to the wing 14. The particular device shown is designed to be supported on the floor below the wing tip in such a way that when the device is electrically actuated, its plunger 58 is driven upwardly into impact with the underside of the wing tip. The plunger is returned by gravity or spring action.

Laser 26 and impulsive loading device 56 are actuated in timed relation by a control unit 62. Referring to FIG. 1B, the control unit 62 comprises an electrical pulse generator 64 which is electrically connected through an adjustable time delay circuit 66 to the wing loading device 56 and through two parallel adjustable time delay circuits 68, 70 to the laser power supply 72. The control unit 62 is selectively operable to effect generation of a single output pulse by the pulse generator 64. This output pulse is transmitted to the loading

device and power supply through the delay circuits. Delay circuits 68, 70 are set to different time delays, such that the laser power supply 72 receives two successive input pulses. Each input pulse triggers the power supply to pulse the laser 26, whereby each actuation of the control unit 62 pulses the laser twice. The input pulse arriving at the loading device 56 through the delay circuit 66 effects actuation of the device to extend its plunger 58 into impact with the wing 14.

The time delay circuits 66, 68, and 70 are adjusted to provide time delays such as to effect pulsing of the laser 26 and the wing loading device 56 in predetermined timed relation, as explained below. Each such timed operation of the laser and loading device occasioned by actuation of the control unit 62 is hereafter referred to as an exposure cycle of the inspection apparatus 12. Thus, each actuation of the control unit effects one exposure cycle of the apparatus.

The operation of the inspection apparatus will now be explained. Assuming the apparatus to be placed in the proper position relative to the aircraft wing 14, the weight 54 is applied to the wing tip to exert a static preload on the wing. This preload and the weight of the wing, engines 16, and any other loads on the wing establish an initial static load or stress condition within the wing root region 51.

An exposure cycle of the inspection apparatus 12 is now initiated by actuation of the control unit 62. In the course of this cycle, the laser 26 and wing loading device 56 are pulsed in timed relation to effect recording on the holographic recording plate 30 two successive holograms of the wing surface area 50 and to produce on the wing 14 stress waves which propagate along the wing from its tip through the wing root region 51 containing the surface area 50. These stress waves cause deflection of the wing and produce within its root region, which is already preloaded to an initial stress condition as explained earlier, a dynamic incremental load or stress. In other words, during the course of the exposure cycle, an initial stress condition exists in the wing root region at the start of the cycle and a different stress condition exists in the root region as the stress waves propagate through the region. The incremental stress change which thus occurs within the root region produces within the region an incremental displacement or distortion of the wing structure related to the effective stiffness of the structure.

According to the present invention, pulsing of the laser 26 to record the two holograms and pulsing of the wing loading device 56 to produce a dynamic incremental load on the wing are so timed, by appropriate adjustment of the time delay circuits 66, 68, and 70 that the first hologram is recorded when the wing root region is in one stress condition and the second hologram is recorded when the wing root region is in another stress condition. The resulting double exposed hologram is thus an interferogram containing holographic information representing the deformation or displacement signature of the wing, that is the incremental wing deformation or displacement of the wing, within its root surface area 50, resulting from the difference in the stress conditions existing within the wing root region 51 at the instants of recording the two holograms.

As noted earlier, the above inspection procedure is repeated periodically during the service life of the aircraft to create a collection of successively recorded in-

terferograms representing successive displacement signatures of the wing 14. Each signature is compared with the earlier recorded signatures by holographically reconstructing and comparing their deformation patterns to determine any changes in the signatures, i.e. patterns. Such differences, if any, indicate a change in the structural integrity of the wing. Serious wing damage may be ascertained by proper analysis of the signatures, thus permitting more extensive wing inspection by disassembly and x-ray inspection and wing repair or replacement only when indicated to be necessary by holographic inspection.

It will be apparent that the two successive holographic exposures during each wing inspection exposure cycle may be made at various times in the cycle and that the differing stresses existing in the wing root region 51 during the two exposures will depend on the timing of the exposures. That is to say, the two exposures may be made at various times relative to the propagation of the impulsively produced stress waves along the wing. According to the preferred practice of the invention, the first exposure is made prior to arrival of the stress waves at the wing root region and the second exposure is made at the instant of passage of the waves through this region.

Attention is now directed to FIG. 4 which depicts a deformation pattern such as might be produced by the practice of this invention. This pattern had deformation fringe lines f crossing a lap joint between riveted panels P. This pattern is compared with an earlier deformation pattern of the structure being inspected to determine any changes in the pattern indicating a change in the stiffness and hence structural integrity of the structure. As noted earlier, such pattern changes may take the form of changes in the number, shape, spacing, width, or other characteristics of the fringe lines f. It will be apparent, of course, that each pattern may be analyzed individually in the well known way to detect cracks, loose rivets, and other damage. In FIG. 4, for example, the discontinuity of the fringe lines in the region R indicate such damage.

FIGS. 2 and 3 illustrate a modified holographic inspection apparatus 100 according to the invention. This modified apparatus includes the laser 26, mirror 38, holographic plate holder 34, and control unit 62 of the inspection apparatus shown in FIG. 1. The modified apparatus further comprises a wheeled vehicle 102 mounting the control unit 62 and a hinged boom 104 which is vertically adjustable by hydraulic means (not shown). Swiveled on the upper end of the boom is an adjustable platform 106. The laser 26, mirror 38, and plate holder 34 are adjustably mounted in any convenient way on this platform in the positions shown, such that by proper placement of the vehicle 102 and adjustment of the boom 104, platform 106, laser 26, mirror 38, and plate holder 34, the apparatus 100 may be arranged to record holograms of the structure to be inspected. In FIGS. 2 and 3, for example, the apparatus is set to inspect the root portion of an aircraft wing 14. The modified apparatus operates and is used in the same manner as the inspection apparatus of FIG. 1.

We claim:

1. The method of nondestructively evaluating the structural integrity of a load bearing structure comprising the steps of:
recording on a first holographic recording medium a first hologram of said structure while the latter is in

a first stress condition and a second hologram of said structure while the latter is in a second stress condition to produce a first holographic interferogram for reconstructing a first holographic deformation pattern of the structure; and thereafter recording on a second holographic recording medium a first hologram of said structure while the latter is in said first stress condition and a second hologram of said structure while the latter is in said second stress condition to produce a second holographic interferogram for reconstructing a second holographic deformation pattern of the structure which may be compared with said first deformation pattern to detect differences, if any, in the patterns, such differences being indicative of changes in the structural integrity of said structure in the interval between recording of said interferograms.

2. The method of claim 1 including the additional step of:
stressing said structure in the interval between recording of said interferograms.

3. The method of claim 1 including the additional step of:
subjecting said structure to variable stress in the interval between recording of said interferograms.

4. The method of claim 1 wherein:
said stress conditions are created by static loading of said structure.

5. The method of claim 1 wherein:
said stress conditions are created by subjecting said structure to a first static load during recording of each first hologram and to a second static load during recording of each second hologram.

6. The method of claim 1 wherein:
said stress conditions are created by impulsive loading of said structure.

7. The method of claim 1 wherein:
said stress conditions are created by applying an impulsive load to said structure in such a way as to propagate stress waves through said structure, and recording each set of first and second holograms in rapid succession, whereby said stress waves establish said first stress condition on the structure during recording of the first hologram and said second stress condition in the structure during recording of the second hologram.

8. The method of claim 1 wherein:
said stress conditions are created by combined static and impulsive loading of the structure.

9. The method of claim 8 wherein:
said structure is impulsively loaded by applying an impulsive load to said structure in such a way as to propagate stress waves through said structure, and recording each set of first and second hologram in rapid succession, whereby said stress waves establish said first stress condition on the structure during recording of the first hologram and said second stress condition in the structure during recording of the second hologram.

10. The method of claim 1 wherein:
said structure is an aircraft structure; and
said method comprises the additional step of subjecting said structure to variable stress cycles in the interval between recording of said interferograms.

11. The method of claim 10 wherein:

said structure is subjected to said stress cycles by flying the aircraft during said interval.

12. The method of claim 10 wherein:
said stress conditions are created by static loading of said structure.

13. The method of claim 10 wherein:
said stress conditions are created by subjecting said structure to a first static load during recording of each first hologram and to a second static load during recording of each second hologram.

14. The method of claim 10 wherein:
said stress conditions are created by impulsive loading of said structure.

15. The method of claim 10 wherein:
said stress conditions are created by applying an impulsive load to said structure in such a way as to propagate stress waves through said structure, and recording each set of first and second holograms in rapid succession, whereby said stress waves establish said first stress condition in the structure during recording of the first hologram and said second stress condition in the structure during recording of the second hologram.

16. The method of claim 10 wherein:
said stress conditions are created by combined static and impulsive loading of the structure.

17. The method of claim 16 wherein:
said structure is impulsively loaded by applying an impulsive load to said structure in such a way as to propagate stress waves through said structure, and recording each set of first and second holograms in rapid succession, whereby said stress waves establish said first stress condition in the structure during recording of the first hologram and said second stress condition in the structure during recording of the second hologram.

18. The method of claim 10 wherein:
said stress conditions are created by combined static and impulsive loading of the aircraft structure to simulate the stress on said structure at the instant of touchdown of the aircraft during landing; and
said structure is impulsively loaded by applying an impulsive load to said structure in such a way as to propagate stress waves through said structure, and recording each set of first and second holograms in rapid succession, whereby said stress waves establish said first stress condition in the structure during recording of the first hologram and said second stress condition in the structure during recording of the second hologram.

19. Apparatus for nondestructively evaluating the structural integrity of a structure comprising:
a holographic system including a laser for recording on the same holographic recording medium successive holograms of the structure;
means for impulsively loading said structure; and
means for operating said system and loading means in timed relation in such a way as to record on said medium a first hologram of said structure while the latter is in one stress condition and a second hologram of said structure while the latter is in a second stress condition.

20. Apparatus according to claim 19 including:
a wheeled vehicle carrying said holographic system.

21. Apparatus according to claim 20 wherein:
said vehicle includes an adjustable boom mounting said holographic system.

22. Apparatus according to claim 21 wherein:
said vehicle further includes an adjustable platform on said boom supporting said holographic system.

* * * *

United States Patent [19]

Jacoby et al.

[11] **4,084,427**[45] **Apr. 18, 1978****[54] HOLOGRAPHIC RECORDING INSTRUMENT FOR STRUCTURAL INTEGRITY VERIFICATION AND OTHER APPLICATIONS**

[75] Inventors: Jerold L. Jacoby, Long Beach; William S. Tierney, Palos Verdes Peninsula; James E. Wright, Long Beach; Pravin G. Bhuta, Torrance, all of Calif.

[73] Assignee: TRW Inc., Redondo Beach, Calif.

[21] Appl. No.: 736,923

[22] Filed: Oct. 29, 1976

Related U.S. Application Data

[62] Division of Ser. No. 598,901, Jul. 24, 1975, Pat. No. 4,049,336.

[51] Int. Cl.² G01M 7/00

[52] U.S. Cl. 73/88 A; 73/577; 73/583

[58] Field of Search 73/88 A, 67.3, 91; 356/109

[56] References Cited**U.S. PATENT DOCUMENTS**

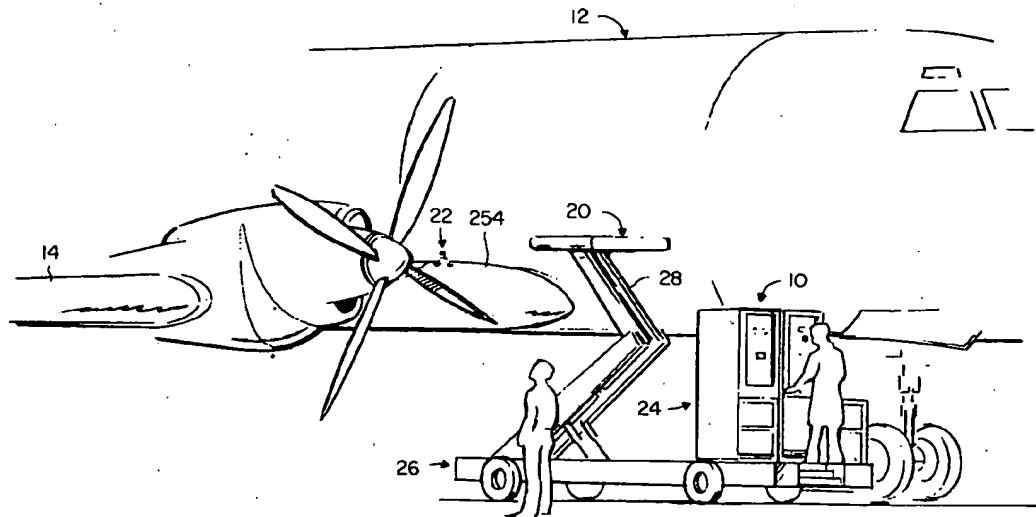
3,631,713 1/1972 Marom et al. 73/67.3
3,911,733 10/1975 Bhuta et al. 73/88 A

*Primary Examiner—Anthony V. Ciarlante
Attorney, Agent, or Firm—John J. Connors; Donald R. Nyhagen; Benjamin DeWitt*

[57] ABSTRACT

An improved holographic recording instrument for recording on a holographic recording medium two successive holograms of the structure under differing stress conditions to produce a holographic interferogram containing information defining a deformation fringe pattern representing the deformations in the structure resulting from the change in stress conditions. A holographic recording unit for the instrument and for general holographic recording use.

3 Claims, 12 Drawing Figures



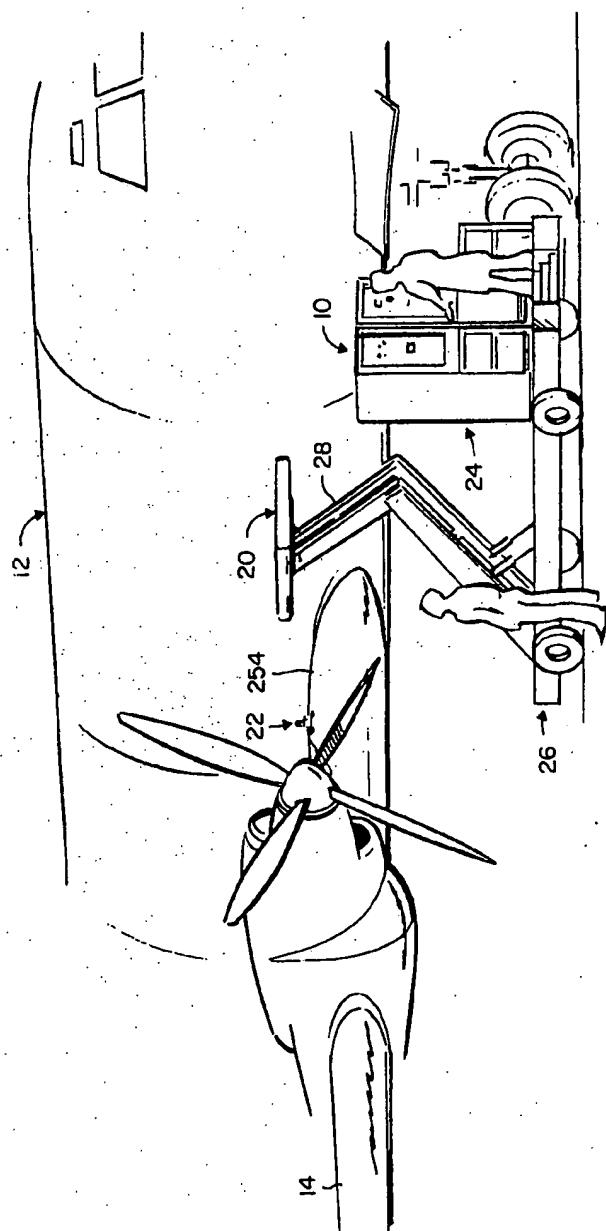


Fig. 1

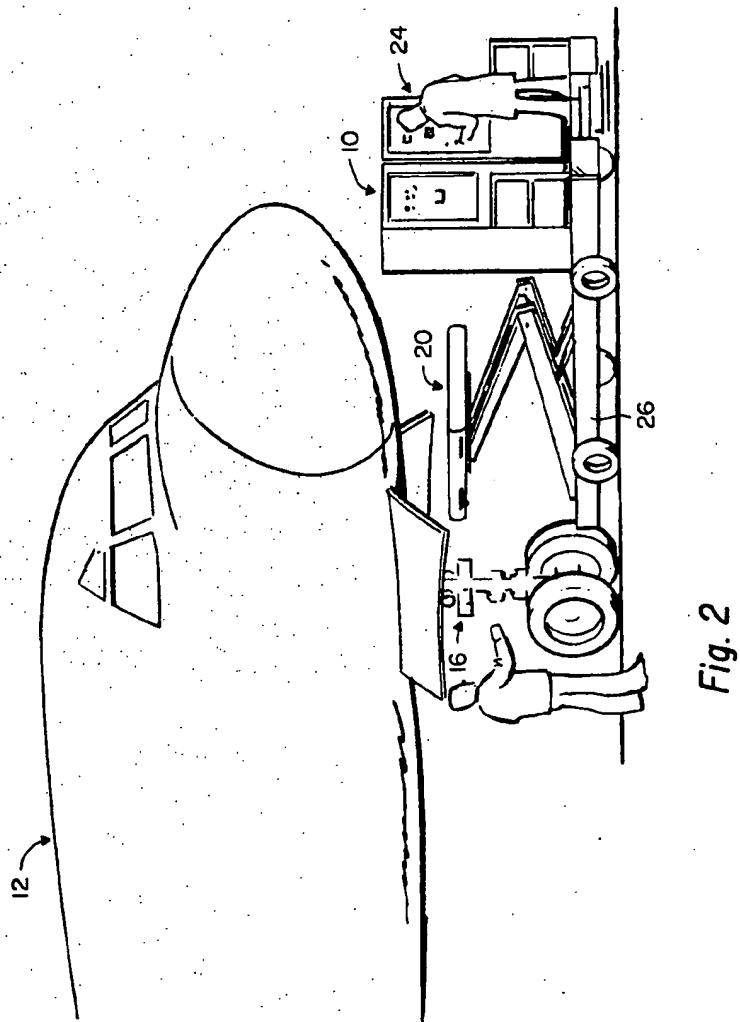


Fig. 2

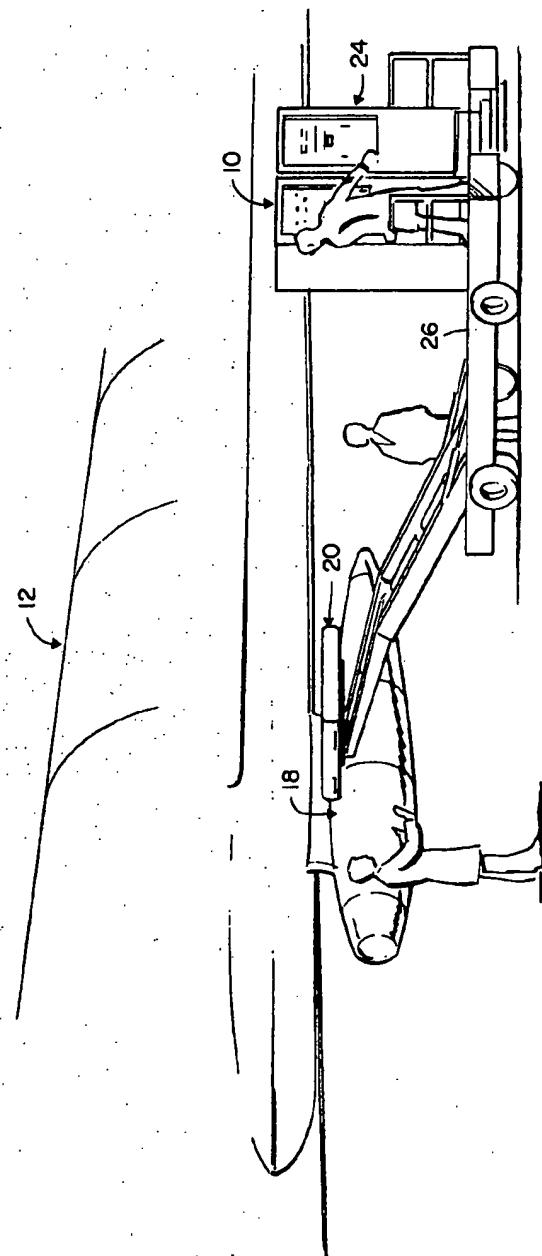


Fig. 3

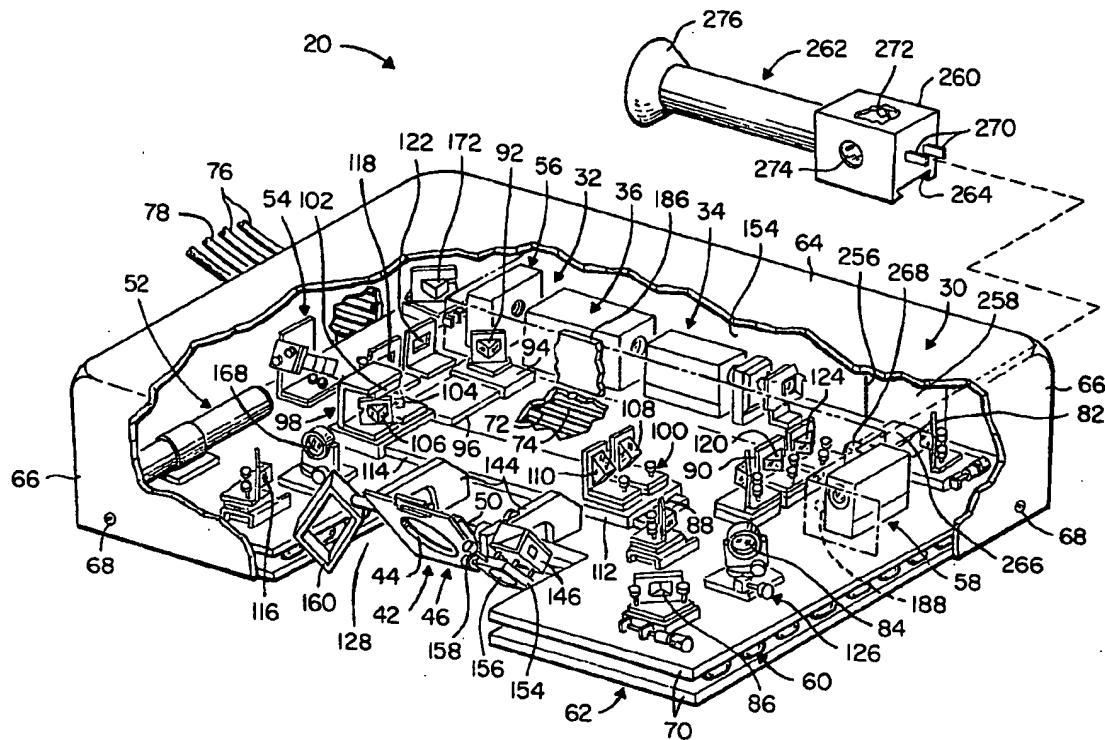


Fig. 4

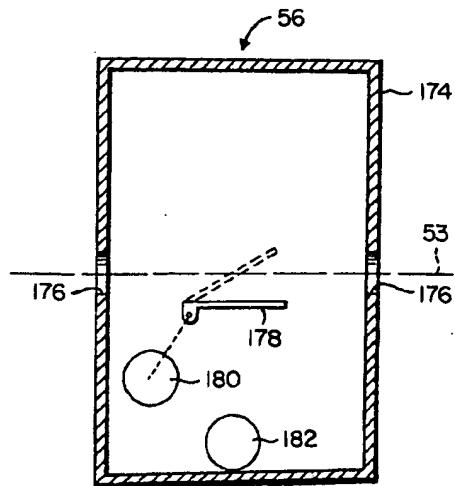


Fig. 9

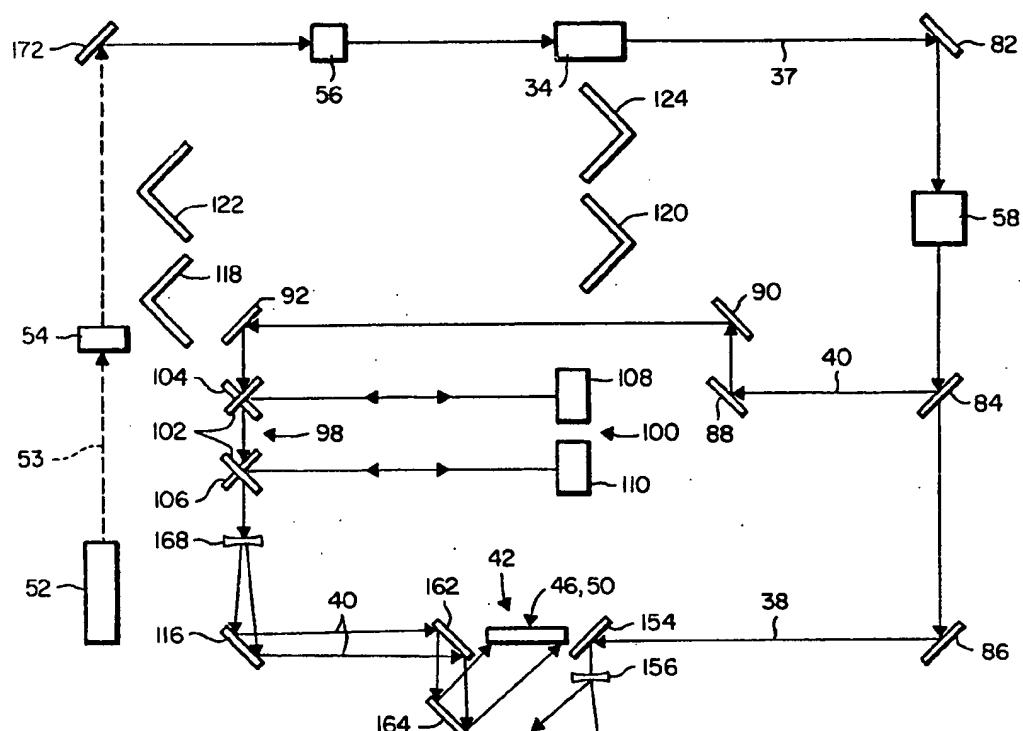


Fig. 5

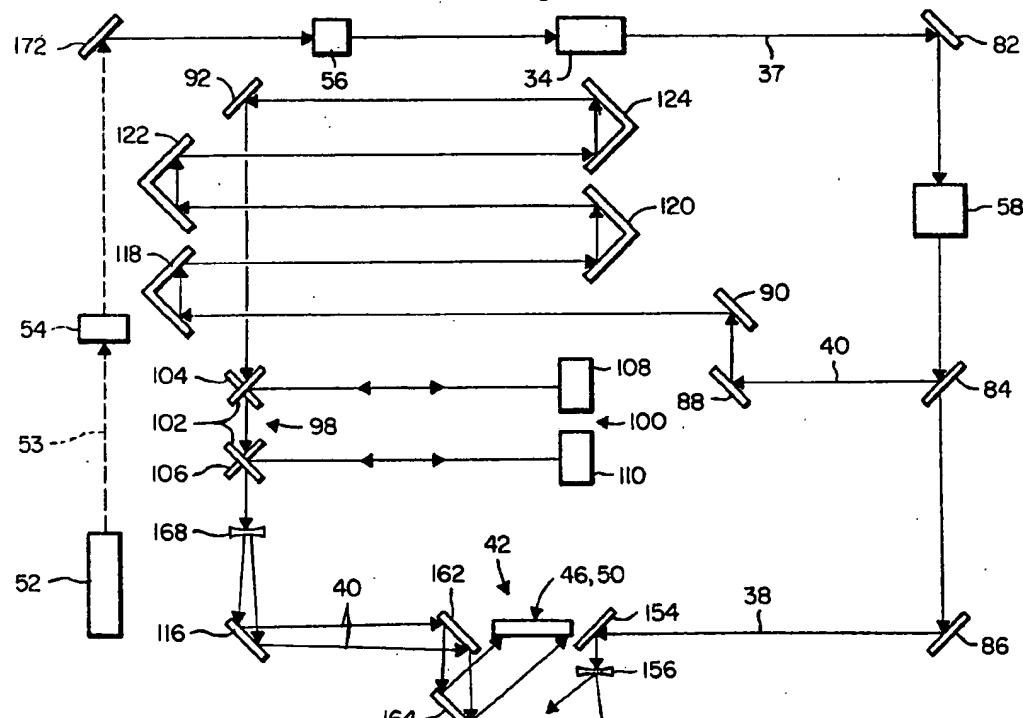


Fig. 6

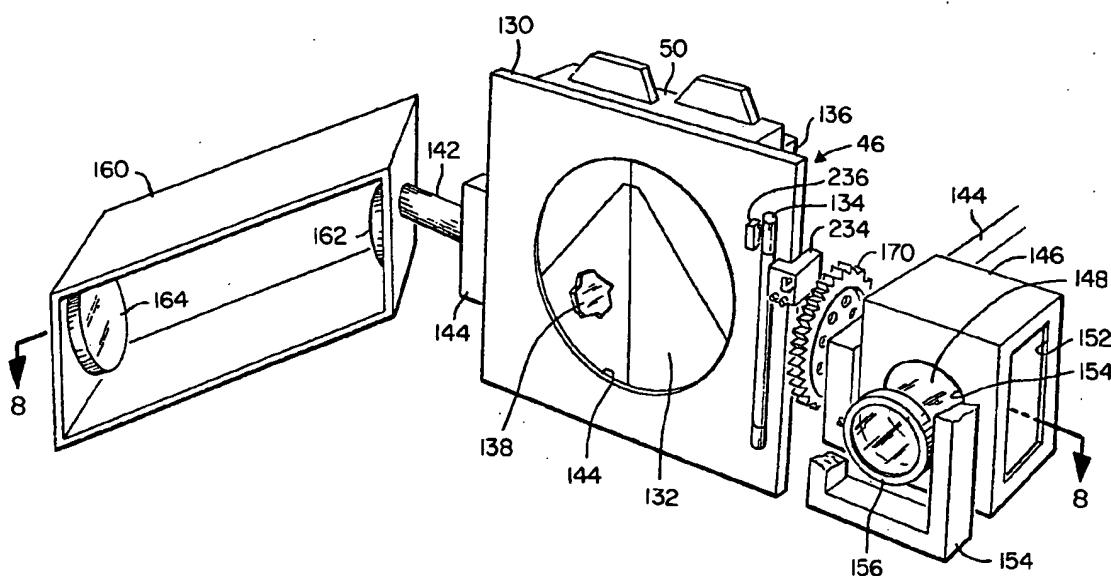


Fig. 7

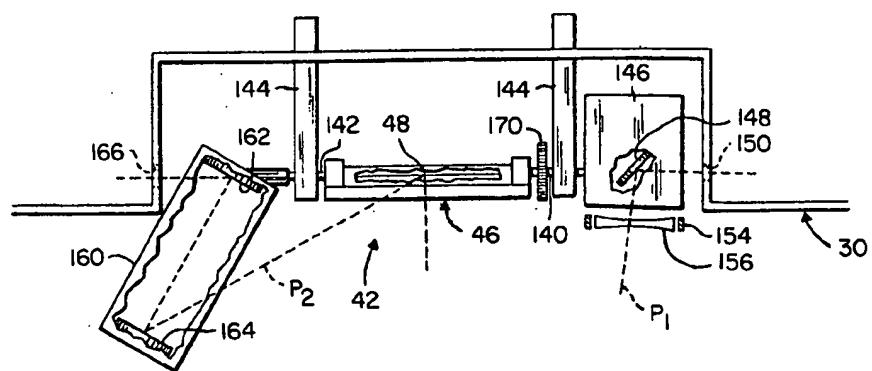


Fig. 8

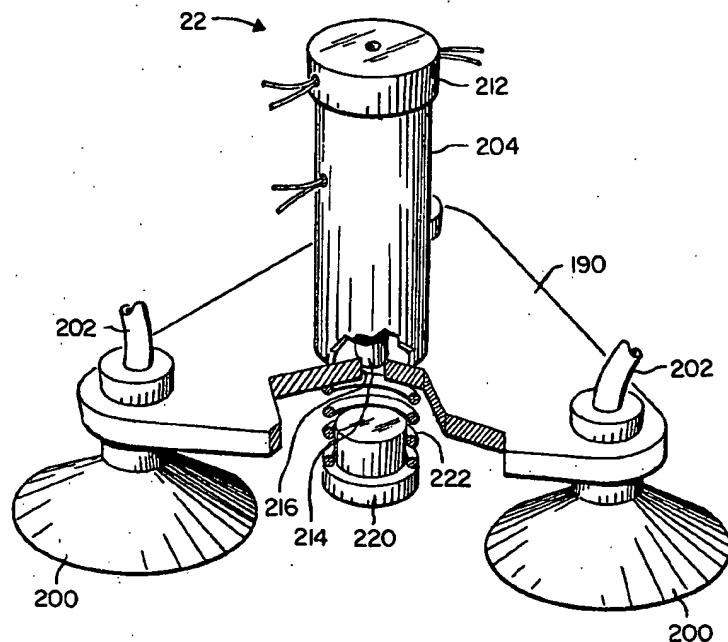


Fig. 10

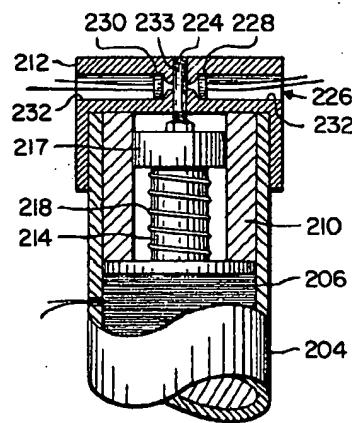


Fig. 11

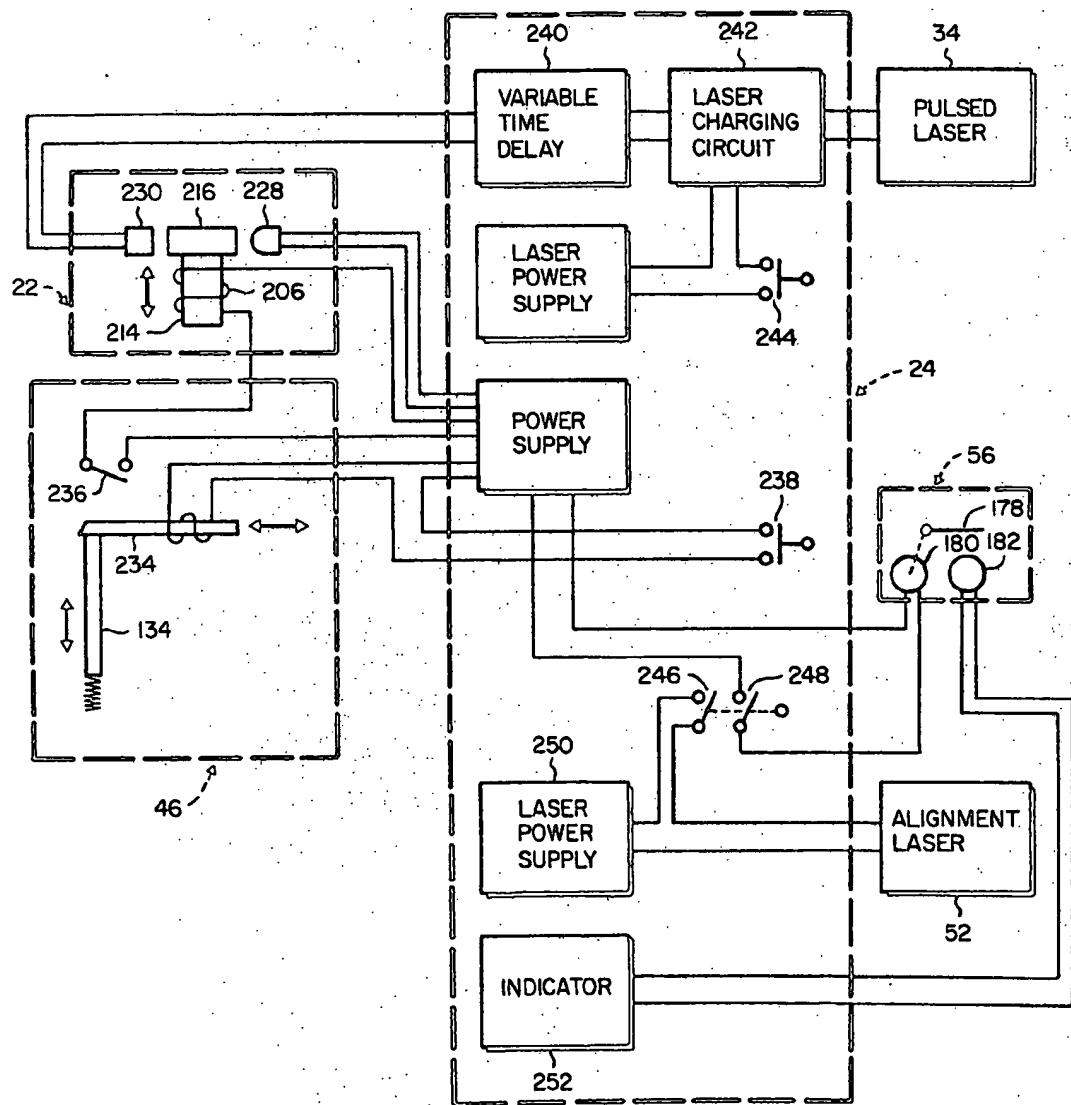


Fig. 12

HOLOGRAPHIC RECORDING INSTRUMENT FOR STRUCTURAL INTEGRITY VERIFICATION AND OTHER APPLICATIONS

The invention herein described was made in the course of or under a contract or subcontract thereunder with the Department of Defense.

This is a division of application Ser. No. 598,901, filed July 24, 1975 now U.S. Pat. No. 4,049,336.

RELATED APPLICATIONS

Reference is made to copending applications Ser. No. 456,998 by Pravin G. Bhuta et al. for "Optical Signature Method and Apparatus for Structural Integrity Verification", U.S. Pat. No. 4,019,374 by William S. Tierney et al. for "Electromagnetic Impulser for Dynamically Loading a Structure", and U.S. Pat. No. 3,993,399 by Jerold L. Jacoby et al. for "Universal Holographic Optics Orientation Assembly."

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to the field of holography and more particularly to a novel holographic recording unit and to a compact mobile holographic instrument embodying the recording unit for evaluating the structural integrity of load-bearing structures utilizing holographic interferometry and other uses.

2. Prior Art

As will become readily apparent from the ensuing description, the recording unit of the invention may be utilized for general purpose holographic recording and the holographic instrument may be utilized for a variety of holographic recording applications. However, the recording unit and holographic instrument are particularly adapted for evaluating the integrity of aircraft structures and other similar redundant load-bearing structures, that is load-bearing structures having multiple load paths. For this reason, the invention will be described in connection with this particular use. In view of the above noted broader utility of the instrument, it will be understood that this described application involving aircraft inspection is purely illustrative and not limiting in nature.

An aircraft wing is a highly redundant load-bearing structure having multiple internal load-bearing members providing multiple load paths through the structure. The wing structure is designed to sustain loads substantially in excess of those which are encountered in normal aircraft service. Over a period of time, however, a wing structure is prone to loss of its structural integrity, that is weakening of its load-bearing members due to fatigue damage, stress corrosion cracking, and other causes. Fatigue damage, of course, involves cracking of the wing load-bearing members, loosening of joints and rivets, and other weakening of the wing structure caused by the frequent load reversals which occur in the structure during flight, landing, and take-off. Stress corrosion cracking occurs in aircraft which operate in an ocean environment and is caused by the corrosive action of salt water. In order to assure continued safe aircraft operation, therefore, it is necessary to periodically evaluate the structural integrity of aircraft wings, as well as other parts of the aircraft, of course.

A variety of inspection and testing techniques have been devised to evaluate the structural integrity of aircraft wings and other aircraft parts. One common inspection technique, for example, involves installing

accelerometers on selected structural members for counting stress reversals experienced by the members. From these counts and a statistical model based on the behavior of the particular aircraft structure of interest and statistical considerations regarding the distribution and size of defects, fatigue damage may be predicted. At appropriate times, the wing structure may be disassembled and subjected to actual fatigue inspection using x-rays or other nondestructive inspection techniques and/or fatigue damage tests. This method of evaluating structural integrity, however, is extremely costly and time consuming. The same applies to the current methods of inspecting aircraft wings and other structures for stress corrosion cracks, which methods require stripping all paint from the surfaces to be inspected, inspection of the surfaces by ultrasonic or other inspection techniques, and repainting of the surfaces. Accordingly, there is a need for an improved nondestructive inspection technique for evaluating the structural integrity of load-bearing structures, particularly highly redundant load-bearing structures, such as aircraft wings and other aircraft structures and parts.

The earlier mentioned copending application Ser. No. 456,998, provides such an improved inspection or structural integrity verification technique, and apparatus for its practice, involving holographic interferometry. This improved inspection technique is based on the fact that any loss of structural integrity, that is weakening, of a load-bearing structure due to fatigue damage, stress corrosion cracking, or other causes reduces the effective stiffness of the structure. Such reduction in stiffness, in turn, changes the deformations which the structure will experience in response to any given loading or stressing of the structure. The improved inspection technique utilizes holographic interferometry to detect such distortion changes and thereby changes in the structural integrity of the test structure.

According to the improved inspection technique, a load-bearing structure is periodically inspected by establishing in the structure two successive predetermined stress conditions of differing magnitude and recording on the same holographic recording medium two successive holograms of the structure while the latter is in these stress conditions. The resulting holographic recording is an interferogram which may be holographically reconstructed to produce a deformation fringe pattern whose fringe lines depict or represent the deformations occurring in the structure due to the change from one stress condition to the other. This inspection procedure is repeated periodically using the same stress conditions, and the deformation fringe patterns of the successive interferograms are compared to determine differences, if any, in the fringe patterns. Such differences, if any, between the successive fringe patterns are indicative of a change in the structural integrity or stiffness of the structure in the intervals between recording of the interferograms.

The two stress conditions required for each periodic inspection of the structure may be established by either or both static or dynamic loading of the structure. According to the static loading procedure, the structure to be inspected is subjected to a given static load, which may be simply the weight of the structure or an additional static load, during recording of the first hologram. The static load on the structure is then changed and the second hologram is recorded. According to the dynamic loading procedure, an impact or impulsive load is applied to the structure to effect propagation of

stress waves through the structure. These stress waves establish a first stress in the structure when the first hologram is recorded and a second stress condition when the second hologram is recorded. According to the combined static and dynamic loading procedure, the structure is subjected to a constant static load in addition to the impulsive load.

The inspection apparatus of the copending application Ser. No. 456,998 for practicing the inspection technique of the application comprises a holographic recording unit for recording successive holograms of a selected region of the structure under inspection, an impulser for dynamically loading the structure to propagate stress waves through the region, and control means for operating the recording unit and impulser in timed relation such that each pair of successive holograms are recorded under different stress conditions in the region of interest of the structure to produce a holographic interferogram defining a deformation fringe pattern. As described above, the deformation fringe patterns of successive interferograms are compared to determine a change, if any, in the structural integrity of the structure.

SUMMARY OF THE INVENTION

According to one of its aspects, this invention provides an improved holographic recording unit for general holographic and holographic interferometric recording purposes. This recording unit has a mounting base mounting a pulsed laser holographic recording system for illuminating a holographic recording field in front of the unit with a scene beam and illuminating with reference beam a holographic recording medium positioned in a holder, hereafter referred to for convenience as a film holder, mounted on the front of the instrument. The recording medium, referred to herein as film, is positioned with its sensitive surface facing the recording field, such that recording operation of the unit with a subject positioned in the field effects recording of a hologram of the subject on the film. This recording unit has several features which adapt it to its intended purposes. These features include a unique arrangement for adjusting the position or direction of the holographic recording field relative to the recording unit mounting base to permit the unit to be "pointed" or "aimed" toward subjects in different directions without moving the entire unit; an arrangement for adjusting the holographic optics to "focus" the recording unit at different distances; a unique arrangement for both thermally stabilizing the holographic optics and maintaining a moisture-free environment about the optics; a unique film shutter and laser control arrangement for operating the shutter and holographic laser in timed relation to record a hologram; and the overall arrangement of the recording unit whereby that latter is readily portable from one location to another and is easily installed for use at each location. Other features of the recording unit will also appear as the description proceeds.

According to another aspect of the invention, the latter provides an improved holographic recording instrument including the holographic recording unit for structural integrity evaluation, such as non-destructive evaluation of load bearing structures and strain mapping of complex structures. Another use of the instrument involves practicing the structural integrity verification or inspection technique of the copending application Ser. No. 456,998.

This instrument includes, in addition to the recording unit, an impulser for dynamically loading the structure under inspection to propagate stress waves through the structure, and control means triggered by the film shutter of the recording unit for operating the impulser and holographic laser in timed relation to produce the interferograms, with their deformation fringe patterns involved in inspection technique. The instrument is readily portable from one inspection site to another and is quickly and easily set up at each site. The instrument is described in connection with inspecting aircraft structures for structural integrity.

BRIEF DESCRIPTION OF THE DRAWINGS

- 15 FIG. 1 is a perspective view illustrating the manner of using an optical signature instrument according to the invention for inspecting an airplane wing;
- 10 FIG. 2 is a perspective view illustrating the manner of using the instrument for inspecting an airplane nose area;
- 20 FIG. 3 is a perspective view illustrating the manner of using the instrument for inspecting an airplane jet engine;
- 25 FIG. 4 is a perspective view of a holographic recording unit of the instrument;
- FIGS. 5 & 6 are optical diagrams of the recording unit in two different optical settings;
- 30 FIG. 7 is a perspective view of an adjustable optics assembly of the instrument;
- 35 FIG. 8 is a section through the assembly taken on line 8 — 8 in FIG. 7;
- FIG. 9 is an enlarged section thru a laser beam intensity sensing unit of the instrument;
- FIG. 10 is a perspective view of an impulser used in the instrument;
- 35 FIG. 11 is a fragmentary section through the impulser;
- FIG. 12 is an electrical diagram of the instrument.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring first to FIGS. 1-3 of the drawings, there is illustrated a holographic instrument 10 according to the invention being used to practice the inspection technique of copending application Ser. No. 456,998 for inspecting a variety of structures of an airplane 12, such as the wing 14 in FIG. 1, the nosewheel gear 16 in FIG. 2, and the jet engine nacelle 18 in FIG. 3.

In general terms, the holographic instrument 10, hereafter referred to as an optical signature instrument, comprises a holographic recording unit 20, an impulser 22, and a control unit 24. Instrument 10 operates in a manner which will be described in detail later. Suffice it to say here that the operation involves actuation of the recording unit 20 and impulser 22 in timed relation to impulsively load the aircraft structure being inspected and thereby produce stress waves which travel through the structure, and to record two successive holograms of a selected region of interest of the structure under differing stress conditions in the region resulting from the passage of the stress waves through the region. These two holograms are recorded on the same holographic recording medium or film to produce a double exposure hologram or interferogram containing a deformation fringe pattern representing the surface displacements produced in the region by the change in stress conditions. This procedure is repeated periodically on an aircraft structure to yield a set of interferograms

whose fringe patterns may be compared to evaluate the structural integrity of the aircraft structure.

The holographic recording unit 20 and control unit 24 are mounted on a truck 26 having a hoist 28 which supports the recording unit. The truck is movable and the hoist may be raised and lowered to locate the recording unit in a desired position relative to the aircraft structure to be inspected. FIGS. 1-3, for example, illustrate typical operational placements of the recording unit. The impulser 22 is placed on or attached to the structure to be inspected for impulsively loading the structure, as explained later.

It is worthwhile to again point out here that while the holographic recording unit 20 is described in connection with its use for structural integrity evaluation of an airplane, the unit may be used by itself as a general purpose holographic recording instrument for recording either simple holograms or interferograms of any subject.

Turning to FIGS. 4-9, the holographic recording unit 20 comprises a housing 30 containing a pulsed laser holographic recording system 32. This recording system includes a pulsed laser 34, holographic optics 36 for splitting the pulsed laser output beam 37 into an internal scene beam 38 and an internal reference beam 40, and a universal optics assembly 42 which receives the beams and directs the scene beam outwardly from the recording unit along an external beam path P_1 to illuminate the aircraft structure to be inspected (or other subject of interest). The optics assembly directs the reference beam 40 along an external path P_2 toward the aperture 44 of a shutter 46 on the assembly to illuminate, when the shutter is open, a holographic recording medium or film contained in a film holder 50 removably mounted on the rear side of the shutter.

As will be explained in more detail later, the universal optics assembly 42 is pivotally mounted on the housing 30, about an axis parallel to the front edge of the housing in FIG. 4, to angularly adjust the external scene beam path P_1 , reference beam path P_2 , shutter 46, and film holder 50 in unison relative to the housing. Thus, pivotal movement of the optics assembly rotates the external scene beam path P_1 in a vertical plane relative to the housing 30. The shutter 46, film holder 50 and external reference beam path P_2 rotate with the optics assembly so that the shutter aperture 44 always faces in the direction of the external scene beam path, and the external reference beam path P_2 is always directed toward the aperture, throughout the range of pivotal movement of the optics assembly.

It is worthwhile to note here that the shutter 46 is provided to enable operation of the holographic recording unit 20 in ambient light. However, the unit is capable of operation in the dark without the shutter, as will appear from the ensuing description. Moreover, while the pivotal mounting of the optics assembly performs a highly useful purpose, to be described shortly, it is not essential to the operation of the unit, as will be explained later.

In addition to the above basic elements, the holographic recording system 32 also includes a c-w alignment laser 52 for directing an alignment laser beam 53 through the pulsed laser 34 and then through the holographic optics 36 along the same path as the pulsed laser beam, and alignment means 54 for precisely aligning the path of the alignment beam with the path of the pulsed laser beam, such that when the alignment laser is activated, the optical assembly 42 directs the alignment

beam outwardly from the recording unit along the same path P_1 as the scene beam 38 of the pulsed laser. Between the lasers 34 and 52 is a shutter-sensor unit 56 which, when open, passes the alignment beam to the pulsed laser 34, as described, and when closed acts to sense the intensity of the pulsed laser beam. Located in the common internal beam path of the lasers 34 and 52 is a laser amplifier 58. The recording unit also includes a combination temperature control-purge system 60 for maintaining a relatively constant temperature in and purging moisture, dust, etc. from the housing 30.

Briefly, in operation of the holographic recording unit 20 in the optical signature instrument 10, the recording unit is mounted on the hoist 28 of the instrument truck 26, and the latter and hoist are positioned to locate the recording unit in proper holographic recording position relative to the selected aircraft structure to be inspected, as shown in FIGS. 1-3, for example. The alignment laser 52 is then activated with the shutter-sensor unit 56 open to produce a c-w alignment laser beam which is directed outwardly from the recording unit toward the selected aircraft structure, along the path P_1 of the pulsed laser scene beam 38, by the universal optics assembly 42 of the recording unit. The optics assembly is rotatable about its pivot axis to aim the alignment beam, and thereby the optics assembly as well as the holographic system 32 as a whole, at a selected region of interest of the aircraft structure. It is worthwhile to note here that this adjustability of the optics assembly 42 constitutes an important feature of the invention which enables pointing or aiming of the holographic system 32 at a selected region of interest of the aircraft structure without adjustment of the entire recording unit.

After the recording unit 20 has been properly positioned relative to and aimed at the region of interest of the aircraft structure to be inspected, the unit is operated in its recording mode to record a double exposure hologram or interferogram of the region. As will appear from the later description, operation of the recording unit in its recording mode involves initial actuation of the optics assembly shutter 46 to momentarily open its aperture 44. This shutter actuation triggers actuation of the impulser 22 to impulsively load the aircraft structure and thereby produce stress waves in the structure which travel through its region of interest to be inspected. Actuation of the impulser, in turn, triggers pulsing of the pulsed laser 34 twice in rapid succession while the shutter 46 is still open and in timed relation to the passage of the stress waves through the structure to record on the film in the film holder 50 two successive holograms of the region of interest under differing stress conditions in the region resulting from the passage of the stress waves through the region. As noted earlier, the resulting double exposure hologram is an interferogram containing a deformation fringe pattern representing the surface displacements or deformations produced in the region by the stress wave induced stress changes.

Referring now in greater detail to the illustrated holographic recording unit 20, the unit housing 30 has a double-walled base plate 62 and a removable cover 64 with depending side walls 66 which are releasably secured to the base plate by screws 68 or the like. Base plate 62 comprises a pair of spaced parallel plate members 70 between which are disposed a pair of tubes 72 and 74. These tubes are arranged in heat transfer relation to one another and extend back and forth in serpentine fashion between the plate members so as to encom-

pass virtually the entire surface area of these members. Connected to the ends of tube 72 are hoses 76 for circulating a constant temperature fluid, such as water, at approximately room temperature through the tube. Connected to one end of tube 74 is a hose 78 for circulating a dry gas, such as nitrogen, through the tube. As will be explained presently, the opposite end of the dry gas tube 74 opens to the interior of the housing 30 above the base plate 62 for exhausting the gas into the housing. The gas then flows through the housing and finally exhausts to atmosphere through a vent port 80 in the housing cover 64.

The above described arrangement for circulating the constant temperature fluid and dry gas through the housing 30 constitutes the temperature control and purge means 60 referred to earlier. Thus, during its passage through the tube 74, the gas undergoes heat transfer with the constant temperature fluid in the tube 72 and hence emerges into the housing 30 approximately at the temperature of the fluid. During its flow through the housing, the gas provides a relatively constant temperature atmosphere within the housing and purges moisture, dust, and the like from the housing. Moreover, the gas maintains the interior of the housing at a pressure slightly greater than ambient pressure to prevent the entrance of dust into the housing.

The pulsed laser 34 is mounted on the base plate 62 along and with its axis generally parallel to the rear edge of the plate. This laser is preferably a pulsed ruby laser, although other pulsed lasers may be used, and is conventional so that no further description of the laser is necessary. The laser output beam 37 emerges from the right end of the laser in FIG. 4.

As noted earlier, the laser beam 37 is split into scene and reference beams 38 and 40 by the holographic optics 36, which will now be described by reference to FIGS. 4-6. These optics include a number of optical reflectors which are actually prisms, as shown in FIG. 4, but which may be, and for convenience are shown in FIGS. 5 and 6 as mirrors. In the following description of the optics, these reflectors are referred to as reflectors.

Turning now to FIGS. 4-6, the holographic optics 36 include a reflector 82 at the rear right hand corner of the base plate 62 which reflects the laser output beam 37 forwardly, along the right hand side of the plate, through the laser amplifier 58 to a beam splitter 84 on the plate. This beam splitter splits the beam 37 into the scene beam 38 and reference beam 40. Scene beam 38 passes through the beam splitter 84 to a reflector 86 at the right front corner of the base plate which reflects the beam to the left toward and along the pivot axes of the universal optics assembly 42, soon to be described. The reference beam 40 is reflected to the left from the beam splitter 84 to a reflector 88 and then rearwardly to a reflector 90, both mounted on the base plate. The reference beam is again reflected to the left from the reflector 90 along a path which intersects the fore or aft direction line of movement of an adjustable reflector 92.

Reflector 92 is mounted on a slide 94 which is movable back and forth along a guide 96 fixed to and extending in the fore and aft direction of the base plate 62. Reflector 92 is adjustable to its forward position of FIG. 5 and to its intermediate broken line and rearward solid line position of FIG. 6. In its forward position of FIG. 5, the reflector 92 is situated in the path of the reflected reference beam 40 from reflector 90 and reflects the beam forwardly to a fixed reflector assembly 98 on the

base plate 62 which cooperates with an adjustable reflector assembly 100. Fixed reflector assembly 98 comprises an upper horizontal corner reflector 102 and two lower reflectors 104 and 106. The adjustable reflector assembly 100 comprises a pair of vertical corner reflectors 108 and 110 mounted on a slide 112 which is movable along a guide 114 fixed to and extending crosswise of the base plate 62.

The adjustable reflector 92 and the reflector assemblies 98 and 100 are optically aligned in such a way that when the reflector 92 is set in its position of FIG. 5, the reference beam 40 incident on the reflector is reflected forwardly to reflector 104, then to the right to the lower reflecting surface of corner reflector 108, the upwardly to the upper reflecting surface of the latter reflector, then to the left to the rear reflecting surface of corner reflector 102, then forwardly to the front reflecting surface of the latter reflector, then to the right to the upper reflecting surface of corner reflector 110, then downwardly to the lower reflecting surface of the latter reflector, then to the left to reflector 106, and finally forwardly from the latter reflector to a reflector 116 on the base plate 62. The reflector 116 reflects the reference beam 40 to the right toward and along the pivot axis of the universal optics assembly 42.

In the rearward position of reflector 92 shown in FIG. 6, the reference beam 40 from reflector 90 impinges a corner reflector 118 and is then reflected to the right to corner reflector 120, then to the left to corner reflector 122, then to the right to corner reflector 124, and finally back to the left to adjustable reflector 92. The reference beam is reflected forwardly from the reflector 92 to the fixed reflector assembly 98, and then back and forth between this assembly and the adjustable reflector assembly 100 and finally to the reflector 116 in the same manner as described above in connection with FIG. 5. In the intermediate position of reflector, the reference beam reflects from corner reflector 120 to reflector 92 and then to reflector assembly 98. In each position or setting of the adjustable reflector 92, therefore, the output beam 37 from the pulsed laser 34 is split into the scene and reference beams 38 and 40 which are finally directed toward the universal optics assembly 42 from opposite sides and along the pivot axis of the assembly. It will be further understood that adjustment of the reflector 92 between its two settings provides a coarse or gross adjustment of the reference beam path length, while adjustment of the reflector assembly 100 along its guide 114 toward and away from the fixed reflector assembly 98 provides a fine reference beam path length adjustment. The individual fixed reflectors are provided with adjustment means 126 for initially aligning the holographic optics.

As noted earlier, the universal optics assembly 42 receives the scene and reference beams 38 and 40 and directs the scene beam along the path P₁ to illuminate the aircraft structure to be inspected (or other subject of interest) and the reference beam along the path P₂ to illuminate the film 48 in the film holder 50 when the shutter 46 is open. This optics assembly will now be described by reference to FIGS. 4-8. It is important to note here that the optics assembly 42 per se constitutes the subject matter of copending application Ser. No. 662,185.

The universal optics assembly 42 is situated within a rectangular recess 128 midway along the front side or edge of the recording unit housing 30. The shutter 46 of the optics assembly comprises a conventional basic

shutter structure including an opaque housing 130 containing the aperture 44, which is circular and opens at the front and back sides of the housing, and normally closed shutter blades 132 operable by a shutter actuating mechanism powered by a spring-loaded plunger 134 at the front side of the housing. Depression of this plunger from its normal extended position of FIG. 7 against the action of the plunger spring cocks the shutter in such a way that release of the plunger for spring extension effects momentary opening and then reclosing of the shutter blades 132.

Film holder 50 is mounted behind the basic shutter structure described above. To this end, the shutter housing 130 is equipped at its rear side with guides 136 for slidably receiving the film holder with the film 48 exposed forwardly to the shutter through the open front side of the holder. Extending across the shutter aperture 44, between the shutter blades 132 and film 48, is a filter 138 whose purpose will be explained presently.

Rigidly joined to the vertical edges of the shutter housing 130 and extending outwardly from the housing on a common axis in plane of the film 48 and intersecting the axis of the shutter aperture 44, are a pair of journal or pivot shafts 140 and 142. As may be best observed in FIG. 8, these shafts are journaled in bearing brackets 144 which straddle the shutter 46 and are rigidly attached to the base plate 62, at the rear side of the housing recess 128. Shutter 46 is thus pivotally mounted on the housing 30 on a pivot axis parallel to the front side of the housing. This is the pivot axis of the optical assembly 42 along which the scene and reference beams 38 and 40 are directed toward the assembly by the reflectors 86 and 116, as described earlier in connection with FIGS. 4-6.

Fixed to the right end of the optics assembly pivot shaft 140 at the right side of the adjacent shaft bearing bracket 144 is a reflector housing 146 containing a reflector 148. This reflector receives the scene beam from the reflector 86 along the pivot axis of the optics assembly and through side openings 150, 152 in the housings 30, 146 and reflects the beam forwardly through a front opening 154 in the reflector housing 146. Mounted on the front side of the reflector housing 146 is a support 154 for a scene beam expanding lens 156. The support is provided with means 158 for adjusting the lens for reasons to be explained presently.

Fixed at one end to the left end of the optics assembly pivot shaft 142 is an elongate open sided reflector housing 160 containing at its ends two reflectors 162, 164. Reflector 162 is located at the inner end of the housing, on the pivot axis of the optical assembly 42, and receives the reference beam from reflector 116 along the axis and through a side opening 166 in housing 30 and an open side of the reflector housing. The reflectors 162, 164 reflect the reference beam along the path P₂ toward the shutter aperture 44. Mounted on the base plate 62 just before reflector 116 is an expanding lens 168 which expands the reference beam to illuminate the entire shutter aperture area.

From the foregoing description, it will be understood that the universal optics assembly 42 receives the scene and reference beams 38, 40 along the pivot axis of the assembly and directs the expanded scene beam outwardly along the external beam path P₁ and the expanded reference beam toward the shutter aperture 44. The scene beam reflector 148 and expanding lens 156 are adjusted to align the scene beam path P₁ relative to the axis of the shutter aperture 44 in such a way that the

scene beam 38 will illuminate a field, referred to herein as a holographic recording field, along the axis. Accordingly, pulsing of the laser 34 with the shutter 46 open and a subject situated within the recording field is effective to record on the film 48 a hologram of the subject. This assumes, of course, that the path lengths of the scene and reference beams are properly matched, which is accomplished by adjustment of the reflector 92 and the reflector assembly 100 in the manner explained later. It will be further understood that pivotal adjustment of the universal optics assembly 42 is effective to rotate the scene beam path P₁, reference beam path P₂, and shutter 46 in unison about the assembly pivot axes in a manner which effectively adjusts the position or direction of the recording field, or field of view, of the recording unit without moving the entire unit. This adjustment of the optics assembly is aided by a serrated handwheel 170 fixed to the assembly pivot shaft 140.

Returning now to FIGS. 4-6, it will be recalled that the holographic recording unit 20 includes an alignment laser 52 for directing an alignment laser beam 53 through the pulsed laser 34 along the axis of the pulsed laser beam. This alignment laser is a C.W. laser, such as a He-Ne laser, which is mounted at the front left hand corner of the base plate 62. The alignment beam from the laser is directed rearwardly along the left hand side of the base plate, through the beam alignment means 54 to a reflector 172 at the rear left hand corner of the base plate. The reflector 172 reflects the alignment beam to the right through the pulsed laser shutter-sensor unit 56 and then through the pulsed laser 34. After emerging from the pulsed laser, the alignment beam is directed by the holographic optics 36 along the same path as the pulsed laser beam 37, such that a portion of the alignment beam finally emerges from the recording unit along the path P₁ of the pulsed laser scene beam 38.

The beam alignment means 54 is provided for accurately aligning the alignment beam 53 with the scene beam path P₁. The particular alignment means shown in 40 a conventional beam aligner which is adjustable to adjust the alignment beam both angularly and in translation in any direction relative to the axes of the alignment laser. Alignment of the alignment beam 53 with the scene beam path P₁ is accomplished by removing the beam splitter 84 and the scene beam expanding lens 156 and firing the pulsed laser 34 with a target, such as a photographic film, positioned along the path of the scene beam. Impingement of the scene beam with this target produces a spot on the target at the point of impingement of the beam with the target. Thereafter, the alignment laser 52 is activated to produce the alignment beam 53 which impinges and produces a light spot on the target at the point of impingement of the beam with the target. While the alignment laser is thus activated, the beam aligner 54 is adjusted to bring the light spot of the alignment beam into coincidence with the spot produced by the pulsed laser scene beam, thereby establishing coincidence of the alignment beam with the scene beam path P₁.

Referring to FIG. 9, the pulsed laser shutter-sensor unit 56 comprises a housing 174 having aligned wall openings 176 through which the alignment beam 53 may pass to the pulsed laser 34. Pivotally mounted within the housing 174 is a shutter 178 which is swingable between its full line open position and its broken line closed position by a solenoid actuator 180. In its open position, the shutter permits passage of the alignment beam through the unit 56. In its closed position,

the shutter extends across the axis of the housing openings 176 at approximately a 45° angle. The surface of the shutter which faces the pulsed laser 34 in the closed shutter position is a reflecting surface, such that when the pulsed laser is fired with the shutter closed, the small fraction of the pulsed laser beam which passes through the 99% rear end reflector of the pulsed laser strikes the shutter surface and is reflected downwardly. Mounted in the bottom of the housing 174 is a photodiode detector 182 which receives the reflected beam to sense the amplitude and timing of the laser pulse, for the reasons explained below.

It will be recalled from the earlier description that the holographic recording unit 10 embodies temperature control and purge means 60 for maintaining a constant temperature in and purging moisture, dust, etc. from the housing 30 by passing dry gas, such as nitrogen, through tubes 74 in heat transfer relation to a constant temperature fluid circulating through tubes 72 and then passing the gas through the housing. To this end, the pulsed laser 34, shutter-sensor unit 56, and laser amplifier 58 are disposed in a passage-like space 184 formed in the housing 30 by a wall 186 which extends forwardly from the rear wall of the housing at the left end of the pulsed laser in FIG. 4, then to the right along the front side of the laser, then forwardly along the left side of the laser amplifier, and then to the right to the right side wall of the housing. Wall 186 has a window (not shown) through which the alignment beam 53 from the alignment laser 52 passes to the pulsed laser 34 and an opening 188 through which the output beam from the laser amplifier 58 passes to the beam splitter 84.

After its passage through the tubes 74 in heat transfer relation to the constant temperature fluid in tubes 72, the dry, temperature control-purge gas is discharged with the housing space or passage 184 at the left end of the pulsed laser 34 in FIG. 4 through an opening in the top plate member 70 of the base plate 62. The gas then flows to the right through the rear portion of the passage 184 and finally forwardly through the right hand portion of the passage and then through the wall opening 188 into the main interior space of the housing 30. The gas exits to atmosphere through the housing side wall openings 150, 166 (FIG. 8) and through any leakage spaces which may exist in the housing.

It will be understood, therefore, that during its passage through the housing 30, the dry gas flows over the pulsed laser 34, then over the laser amplifier 58, and finally over the holographic optics 36 in the main interior space of the housing, thereby maintaining a relatively constant temperature above the dew point of the atmosphere. Moreover, the gas purges moisture, dust and the like from the housing and maintains a slight positive pressure in the housing to prevent entrance of 55 dust and moist air into the housing.

The optical signature instrument also includes an impulser 22 for percussively loading the structure to be inspected to produce stress waves in the structure. The particular impulser shown constitutes the subject matter of a Copending application which is now U.S. Pat. No. 4,019,374.

Impulser 22 comprises a generally triangular base plate 190 mounting suction cups 200 at the normally underside of the plate. Extending from each cup is a tube 202 through which the cup may be evacuated. Fixed to and rising from the top side of the plate at its center is a cylinder 204 containing a solenoid coil 206.

At the upper end of the coil is a sleeve 210 within the cylinder. The top of the cylinder is closed by a cap 212.

Slidable in the solenoid coil 206 is a solenoid plunger 214, the lower end of which extends slidably through a bore 216 in the base plate 190. On the upper end of the plunger is a shoulder 217 which slides in the sleeve 210. A spring 218 acting against this shoulder urges the plunger upwardly to its normal retracted position of FIGS. 10 and 11. Energizing of the coil 206 extends the plunger downwardly into impact with an anvil 220 below and attached to the base plate by a spring 222. The cylinder cap 212 has an opening 224. The impulser 22 has means 226 for generating a signal in response to extension of the plunger. The signal generating means shown comprises a light-emitting diode 228 and a photodiode detector 230 mounted in coaxial diametrically opposed bores 232 intersecting the cap opening 224. When the plunger 214 is retracted, an adjustable timing shaft 233 threaded in the plunger covers the bores to block light transmission from the diode to the detector. Extension of the plunger uncovers the bores to permit light transmission to the detector which then generates an output signal. The timing shaft is adjustable to adjust the timing of the signal relative to impact of plunger 214 with anvil 220.

This output signal from the impulser 22 fires the pulsed laser 34. Actuation of the impulser, in turn, is effected by the shutter 46 of the holographic recording unit 20. To this end, the shutter is equipped with a solenoid actuated latch 234 (FIG. 7) for releasably latching the shutter plunger 134 in its cocked position, i.e., the depressed plunger position in which the shutter is cocked, and with a switch 236 which is actuated by the plunger, during its upward extension stroke to open and then reclose the shutter, upon arrival of the plunger at the position where the shutter blades 132 are full open.

Turning to FIG. 12, it will be seen that the shutter latch solenoid 234 is controlled by a switch 238 on the control console 24. The shutter switch 236 is connected 40 to the impulser solenoid coil 206 to energize the latter and thereby extend the impulser plunger 214 when the switch is closed by the shutter plunger 134 in the full open position of the shutter blades 132. The photo diode 230 of the impulser is connected through a variable time delay 240 to a pulsed laser charging circuit 242 in the control console. The charging circuit is charged to condition it to fire the pulsed laser 34 by a switch 244 on the control console and is triggered to actually fire the laser by the output signal generated by the photo diode 230 of the impulser in response to extension of the impulser plunger 214. The alignment laser 52 and the shutter solenoid 180 of the pulsed laser shutter-sensor unit 56 are controlled from the control console by switches 246, 248 which operate together to simultaneously activate the alignment laser power source 250 for operating the laser and the solenoid 180 for retracting the shutter 178 to its solid line position of FIG. 9. The output of the photo diode 182 of the unit is fed to the control console for monitoring the timing and amplitude of the pulsed laser output.

The operation of the optical signature instrument 10 will now be explained in the illustrated context of inspecting the aircraft 12 to determine its structural integrity by the structural integrity verification technique described in copending application Ser. No. 456,998. Assuming that the alignment laser beam 53 has been properly aligned with the pulsed laser beam path in the manner explained earlier, the instrument truck 26 is

situated, and its hoist 28 is vertically positioned, to locate the instrument in the best position for inspection of the particular aircraft structure of interest. Assume, for example, that the upper surface of the aircraft wing root section 254 (FIG. 1) is to be inspected. In this application, the instrument may be located in front of the wing root section with the holographic recording unit 20 elevated to a position somewhat above the level of the wing root section, as shown in FIG. 1.

The recording unit 20 is now aimed or pointed at the upper wing root surface region of interest by activating the alignment laser 52 to project the alignment laser beam 53 along the path P₁ of the pulsed laser scene beam 38 and rotating the optics assembly 42 of the recording unit about its pivot axis to aim the alignment beam at the surface region of interest. It will be understood, of course, that the alignment beam may be so aimed by observing the spot of light produced on the wing surface by the beam and adjusting the optics assembly to locate this spot at the approximate center of the surface region of interest. The alignment laser is then turned off. The path lengths of the pulsed laser scene and reference beams 38, 40 are now matched to the accuracy necessary for instrument operation by measuring the distance from the film 48 to the surface region of interest and adjusting the reference beam path length by adjusting the reflector assembly 100 and/or reflector 92 of the holographic optics 36 to the positions which provide matched path lengths. It will be understood that the reflector 92 provides a coarse or gross path length adjustment and the reflector assembly 100 a fine path length adjustment.

The impulser 22 is placed at some point along the aircraft wing 14 adjacent the wing root surface region of interest, as shown in FIG. 1, and the suction cups 200 of the impulser are evacuated through the tubes 202 by a vacuum source (not shown) to clamp the impulser firmly to the wing. This clamping operation causes the impulser anvil 220 to be clamped firmly between the wing and impulser plate 216.

The shutter 46 of the optics assembly 42 is now cocked by depressing the shutter plunger 134 to its cocked position, against the force of the plunger spring (not shown) the shutter being latched in this position by the solenoid latch 234. Thereafter, the charging circuit 242 for the pulsed laser 34 is energized by the switch 244 and, when fully charged, the holographic recording cycle is triggered by operating the switch 238 to actuate the shutter latch 234 and thereby release the shutter plunger 134 for upward extension by its spring to open and then reclose the shutter blades 132. Upon its arrival at the position where the shutter blades are approximately wide open, the shutter plunger actuates the shutter switch 236 to energize the solenoid 206 of the impulser 22. The impulser plunger 214 is then driven downwardly into impact with its anvil 220 to impulsively or dynamically load the aircraft wing and thereby generate stress waves in the wing which propagate through the wing root section 254.

During its downward travel, the impulser timing shaft 233 uncovers the bore 232 in the impulser cap 212, thereby producing an electrical output signal in timed relation to the plunger impact which triggers the pulsed laser charging circuit 242 through the variable time delay 240 to initiate a pulsed lasing cycle of the laser 34. This laser is conventional, as mentioned earlier, and is presettable by conventional means (not shown) to emit one or more short laser beam pulses in rapid suc-

cession during each lasing cycle. In the particular aircraft inspection application under discussion, the laser 34 is preset to emit two pulses during each cycle.

From the description to this point, it will be understood that actuation of the shutter latch 234 initiates or triggers an operating cycle of the optical signature instrument 10. During this cycle, the shutter 46 opens and closes, the impulser 22 propagates stress waves through the aircraft wing root section 254, and the laser 34 emits two short laser beam output pulses in rapid succession, all in timed relation. Each laser output pulse is split into a scene beam pulse directed along the external beam path P₁ of the holographic recording unit 20 to illuminate the wing root section surface region of interest toward which the recording unit is aimed, in the manner described earlier, and a reference beam pulse directed along the path P₂ toward the shutter aperture 44.

The variable time delay 240 is adjustable to vary the timing of the laser output pulses relative to actuation of the impulser 22 and hence relative to propagation of the impulser generated stress waves through the aircraft wing root section 254. In the aircraft inspection application under discussion, this timing is so adjusted that both output pulses occur while the shutter 46 is substantially wide open and at least the second pulse occurs during propagation of the stress waves through the wing root section surface region of interest. In this regard, it will be understood that the opening and closing movement of the shutter blades 132 occurs relatively slowly compared to the remaining events of the instrument cycle, i.e., impulser actuation and laser output pulses, so that the pulses may be timed to occur while the shutter is wide open.

As further explained in the latter application, since the shutter 46 is open during the occurrence of each laser beam output pulse from the laser 34, each pulse is effective to record on the holographic film 48 a hologram of the wing root section surface region of interest. The resulting hologram, then, is a double exposure hologram. Moreover, since the two holograms are recorded at different instants relative to the propagation of the stress waves through the surface region of interest, the two recordings occur under differing stress conditions in the surface region and thus produce on the film a holographic interferogram containing a deformation fringe pattern representing the deformations resulting from the change in stress conditions between the two recordings, all as explained in the earlier mentioned Copending application Ser. No. 456,998. The foregoing inspection procedure may be repeated periodically to yield a library of interferograms whose deformation fringe patterns may be compared to evaluate or verify the structural integrity of the aircraft.

As mentioned earlier, a light filter 138 extends across the aperture 44 of shutter 46. This filter transmits the pulsed laser beam light but blocks ambient light. Thus, the shutter and filter permit the inspection procedure described above to be performed under ambient light conditions. If the inspection is carried out in the dark, the shutter and filter may be eliminated. In this case, the shutter switch 236 may be replaced by a manual switch for triggering the operating cycle of the optical signature instrument. During the instrument operation, the gas purge and temperature control means 60 maintain a constant temperature, moisture and dust free atmosphere in the housing 30 of the recording unit 20.

It will be evident at this point that the capability of adjusting the optics assembly 42 of the holographic

recording unit 20 to aim or point the unit at a selected aircraft structure of interest without adjusting the housing 30 of the unit uniquely adapts the present optical signature instrument 10 to inspection of virtually any part of the aircraft 12. FIG. 2, for example, shows the instrument in position for inspecting the nosewheel gear or adjacent underseal of the fuselage. FIG. 3 shows the instrument in position for inspecting a jet engine nacelle. In each case, of course, the impulser 22 will be mounted in an appropriate position on the structure to be inspected.

While the instrument 10 has been described in connection with its use for inspecting aircraft, the instrument obviously may be used to inspect virtually any type of load bearing structure. Moreover, the instrument may be used without the impulser 22 and with the laser set to single pulse for recording simple holograms of any subject.

In order to permit alignment of the pulsed laser 34, the back wall of the recording unit housing 30 is provided with an opening 256 between the laser and the rear reflector 82. This opening is closed by a door 258 which is hinged along its upper edge to open inwardly for insertion through the opening of a rectangular block-like head 260 on an otherwise conventional autocollimator 262. In the underside of the head is a dovetailed groove 264 for slidably receiving a mating guide 266 on the recording unit base plate 62 to position the autocollimator in the housing. At the inner end of the guide is a stop 268 against which the head abuts when fully inserted into the housing. Extending from the end face of the head 260 are electrical connector prongs 270 which are electrically connected to the collimating lamp (not shown) in the autocollimator and which are engagable in electrical sockets (not shown) in the stop 35 268 to energize the lamp from the recording unit.

The collimating beam from the lamp travels axially through the collimator to a reflector 272 in the autocollimator head 260 and is then reflected at right angles through an aperture 274 in the side of the head along a path which is aligned with the axis of the laser 34 when the autocollimator 262 is positioned in the recording unit 20. Accordingly, the beam is transmitted through the laser rod and is then reflected back through the aperture 274 and then at right angles to the autocollimator eye piece 276 to permit alignment of the laser in the usual way. If desired switch means, such as a Mercury switch, may be mounted on the door 258 to inactivate the lasers 52, 34 for safety purposes when the door is opened by insertion of the autocollimator.

As noted earlier, the holographic recording unit 20 possesses the advantage that it may be pointed or aimed through a range of directions, by adjusting the optics assembly 42, without repositioning the entire unit. This is an advantage, not only because of the problems posed by adjustably supporting the entire unit, which may be relatively large in size and massive, but further because the pockel cell which is commonly used in a pulsed laser is liquid filled and hence would severely restrict

the adjustment range of the entire unit. However, it is considered to be within the scope of the invention to mount the optics assembly elements in a fixed position on the recording unit. With regard to this pointing or aiming adjustment of the recording unit, it is evident that the scene and reference beam paths P_1 , P_2 and the film holder and shutter might be independently adjustable. It is further evident that in some cases only the scene beam path or only the shutter-film holder and reference beam path may be made adjustable, so long as the range of adjustment is sufficiently small to maintain the required holographic recording relation of the recording film 48 to the beam paths, i.e., the relation in which the film continues to be illuminated both by the reference beam and the selected scene beam light from the subject.

What is claimed is:

1. A holographic recording instrument comprising:
holographic recording means including a pulsed laser
for recording on the same holographic recording
medium two successive holograms of a structure of
interest by operating the laser to emit two short
laser pulses in rapid succession, and a shutter for
controlling light passage to said recording medium,
an impulser including a plunger and means for driv-
ing said plunger into impact with said structure for
impulsively loading said structure to generate
stress waves which propagate through and create
varying stress conditions in the structure, and
means for operating said shutter, loading means, and
laser in timed relation in such a way that said laser
pulses occur while said shutter is open and in differ-
ent timed relation to the propagation of said stress
waves through the structure to record on said re-
cording medium a first hologram of said structure
while the latter is in one stress condition and a
second hologram of said structure while the latter
is in another stress condition, said operating means
comprising means for actuating said shutter to
momentarily open the shutter, means for sensing
and actuating said plunger driving means in re-
sponse to a selected condition of said shutter, and
means for sensing and actuating said laser in re-
sponse to movement of said plunger by said
plunger driving means.

2. The holographic recording instrument according
to claim 1 including:

a light filter extending across the shutter aperture
which passes the light of said laser and blocks am-
bient light.

3. The holographic recording instrument according
to claim 1 wherein:

said plunger sensing and laser actuating means in-
cludes adjustable time delay means for adjustably
timing the occurrence of said laser pulses following
movement of said plunger by said plunger driving
means.



US005643476A

United States Patent [19]

Garmire et al.

[11] Patent Number: **5,643,476**[45] Date of Patent: **Jul. 1, 1997****[54] LASER SYSTEM FOR REMOVAL OF GRAFFITI**

[75] Inventors: Elsa Garmire, Manhattan Beach; Katherine X. Liu, Los Angeles; Robert Russell, Manhattan Beach, all of Calif.

[73] Assignee: University of Southern California, Los Angeles, Calif.

[21] Appl. No.: 310,676

[22] Filed: Sep. 21, 1994

[51] Int. Cl. ⁶ B23K 26/04

[52] U.S. Cl. 219/121.68; 219/121.76; 219/121.81; 219/121.83

[58] Field of Search 219/121.6, 121.61, 219/121.62, 121.68, 121.69, 121.7, 121.76, 121.81, 121.82, 121.83, 121.85; 216/4, 65; 134/1; 264/400, 482; 364/474.08

[56] References Cited**U.S. PATENT DOCUMENTS**

Re. 33,777	12/1991	Woodroffe	134/1
4,148,057	4/1979	Jesse	347/232
4,584,455	4/1986	Tomizawa	219/121.68
4,588,885	5/1986	Lovoi et al.	219/121.62
4,665,377	5/1987	Harpaintner	.
4,695,698	9/1987	Mayor et al.	219/121.6
4,756,765	7/1988	Woodroffe	134/1
4,844,947	7/1989	Kasner et al.	.
4,859,075	8/1989	Sutter, Jr. et al.	219/121.61
4,880,959	11/1989	Baum et al.	219/121.85
4,900,891	2/1990	Vega et al.	219/121.6

4,986,664	1/1991	Lovoi	219/121.68
5,040,479	8/1991	Trash	.	.
5,194,723	3/1993	Cates et al.	.	.
5,281,798	1/1994	Hamm et al.	.	.

FOREIGN PATENT DOCUMENTS

2661371	4/1990	France	.
2-263584	10/1990	Japan	.
2246099	1/1992	United Kingdom	.
WO8301400	4/1983	WIPO	.

OTHER PUBLICATIONS

Laser Removal of Graffiti by Katherine Liu and Elsa Garmire, AHMCT Research Report, Sep. 22, 1993.
Elsa Garmire and Katherine Liu, *Summary of Research Effort - Laser Removal of Graffiti*, Jul. 26, 1993, pp. 1-16.

Primary Examiner—Teresa J. Walberg

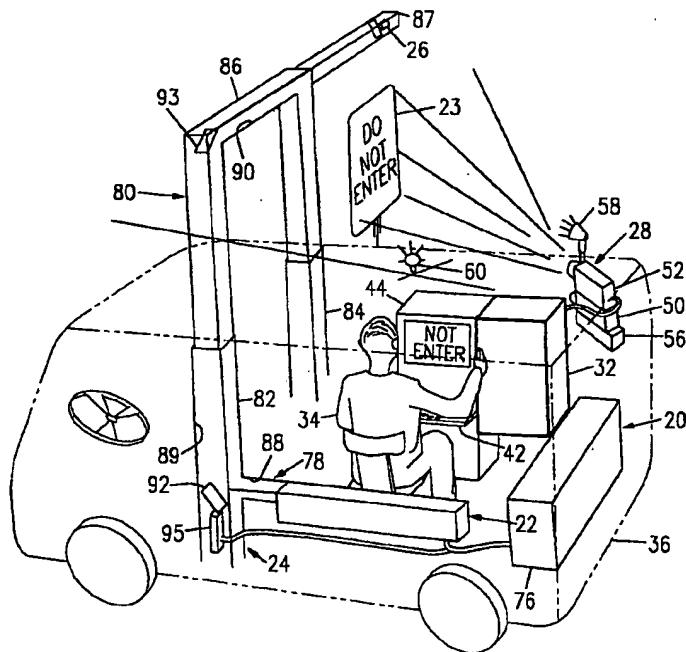
Assistant Examiner—Gregory Mills

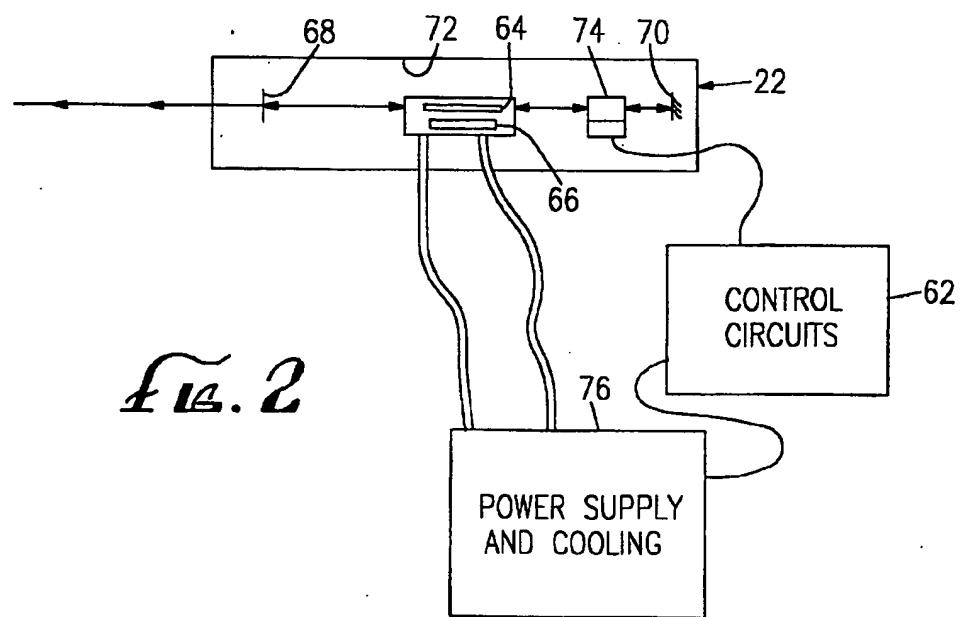
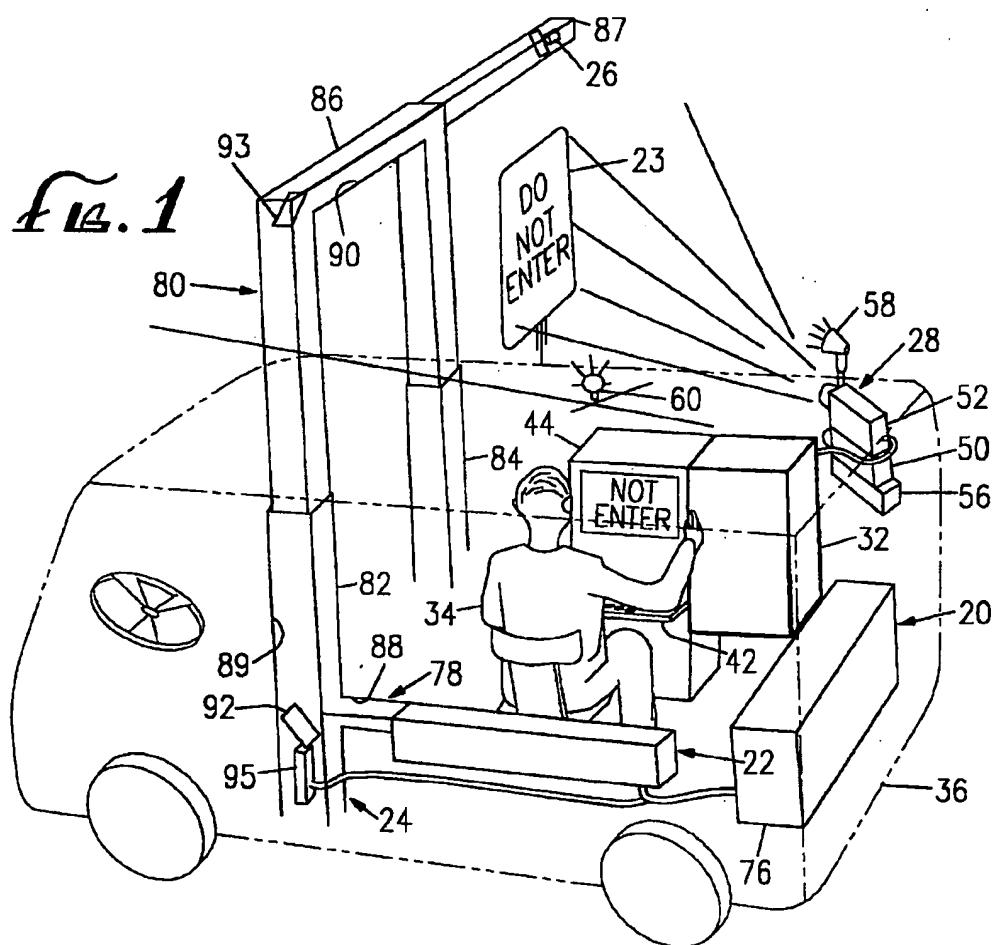
Attorney, Agent, or Firm—Small, Larkin & Kidde

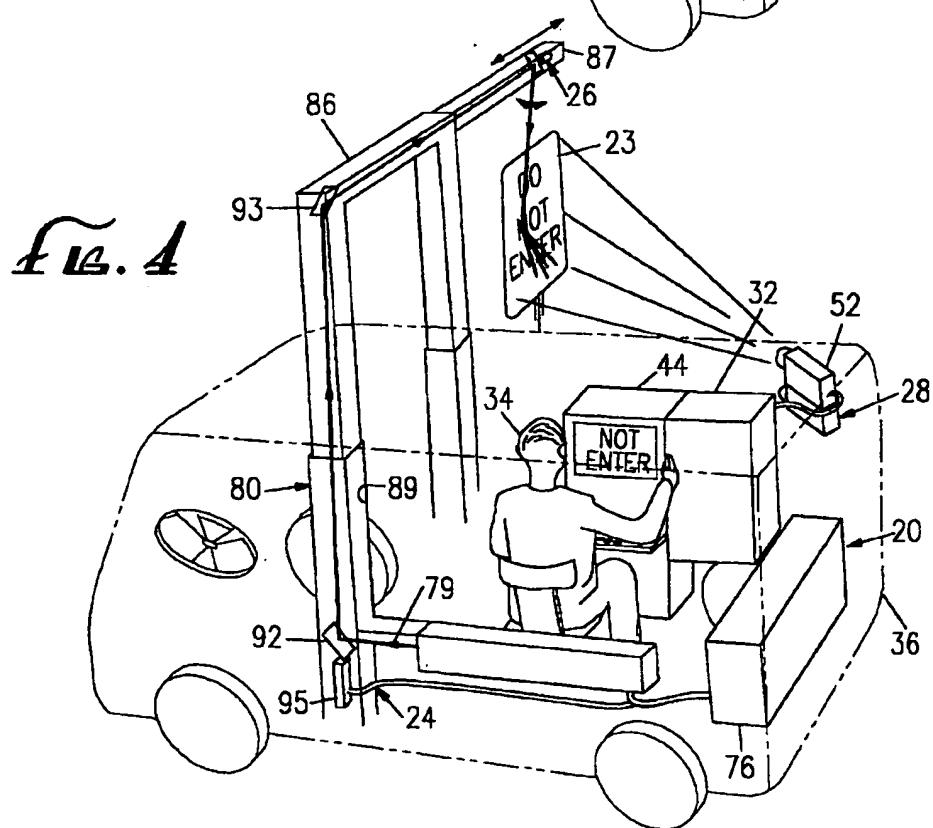
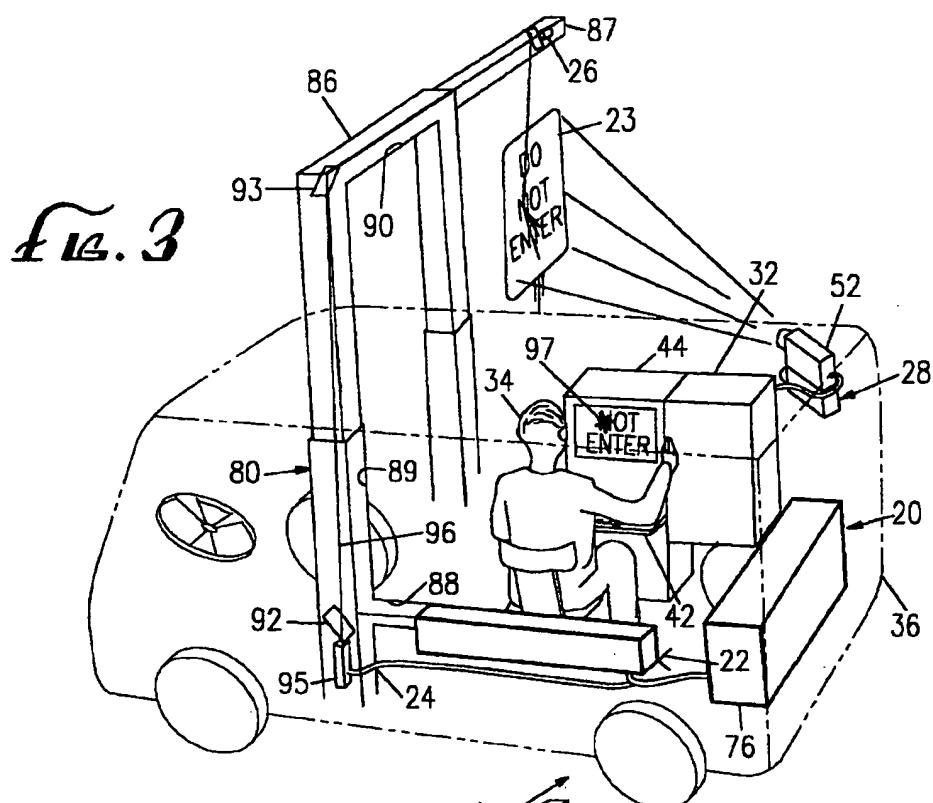
[57] ABSTRACT

A laser system for the removal of graffiti from a retro-reflective highway sign or other surface includes a mobile crane adapted to support a laser scanner and an ablating laser under the control of a computer. An optical sensor and target indicator cooperate to function as a target acquisition device for identifying portions of a highway sign covered with graffiti. Responsive to the target acquisition device, the computer controls the laser scanner and laser to automatically ablate the graffiti covered portions of the highway sign to remove the graffiti. If needed, any remaining graffiti is manually brushed away and the highway sign is polished to restore the retro-reflective properties.

10 Claims, 8 Drawing Sheets







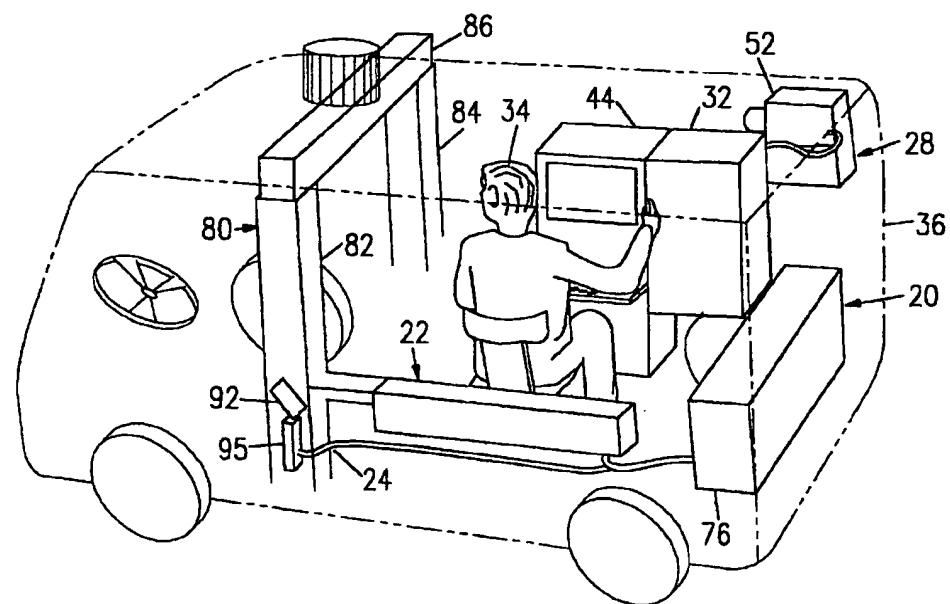
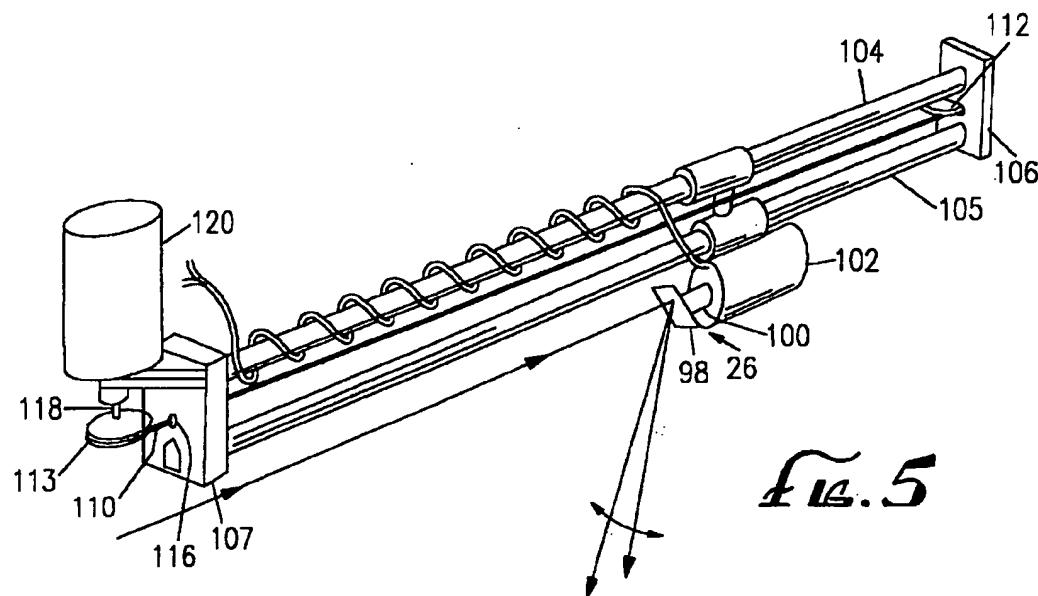


FIG. 6

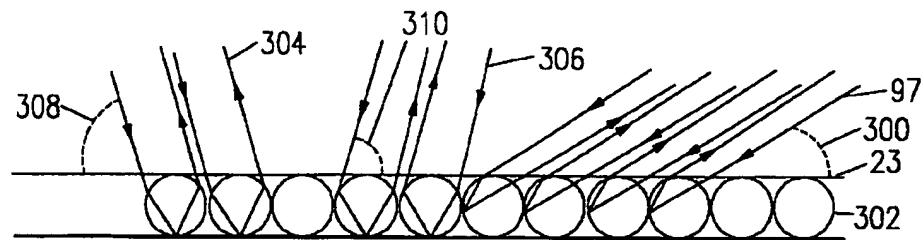


FIG. 7

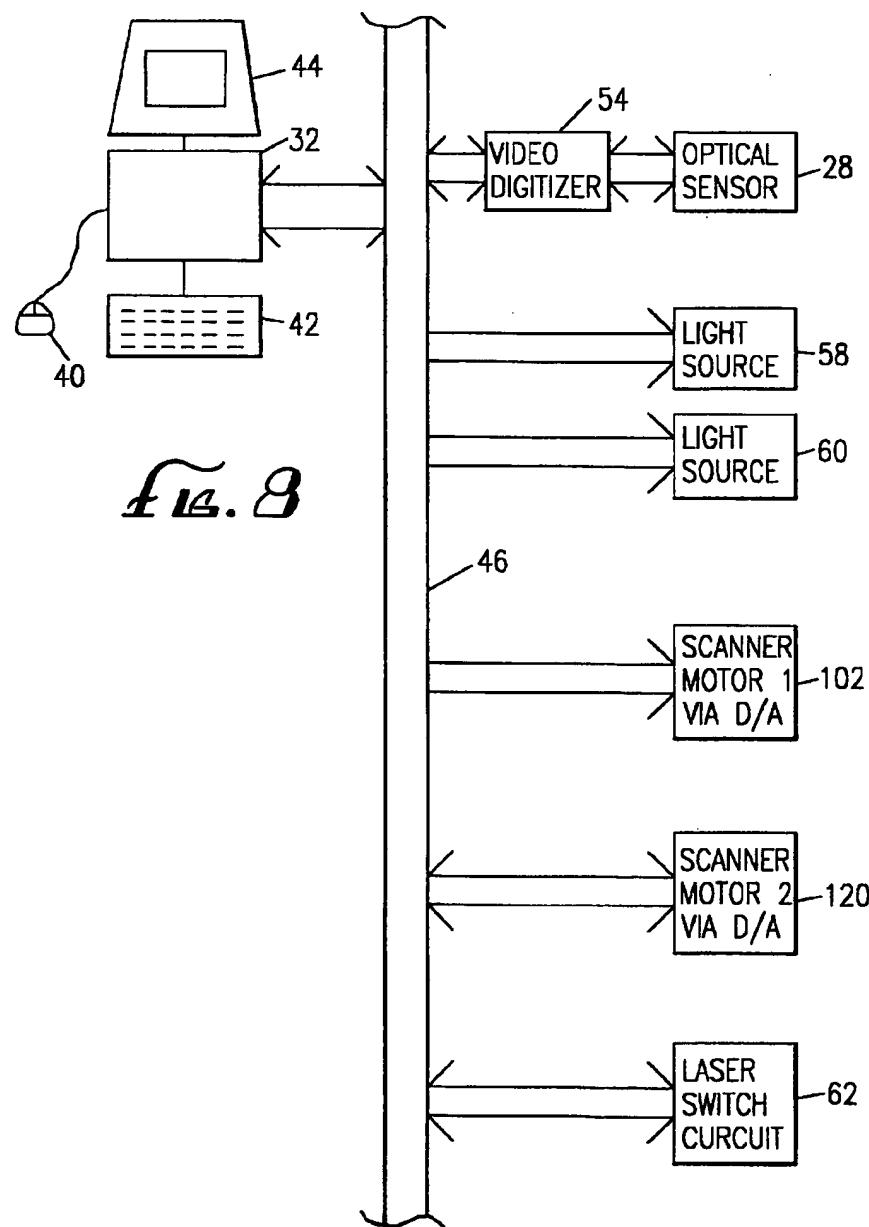
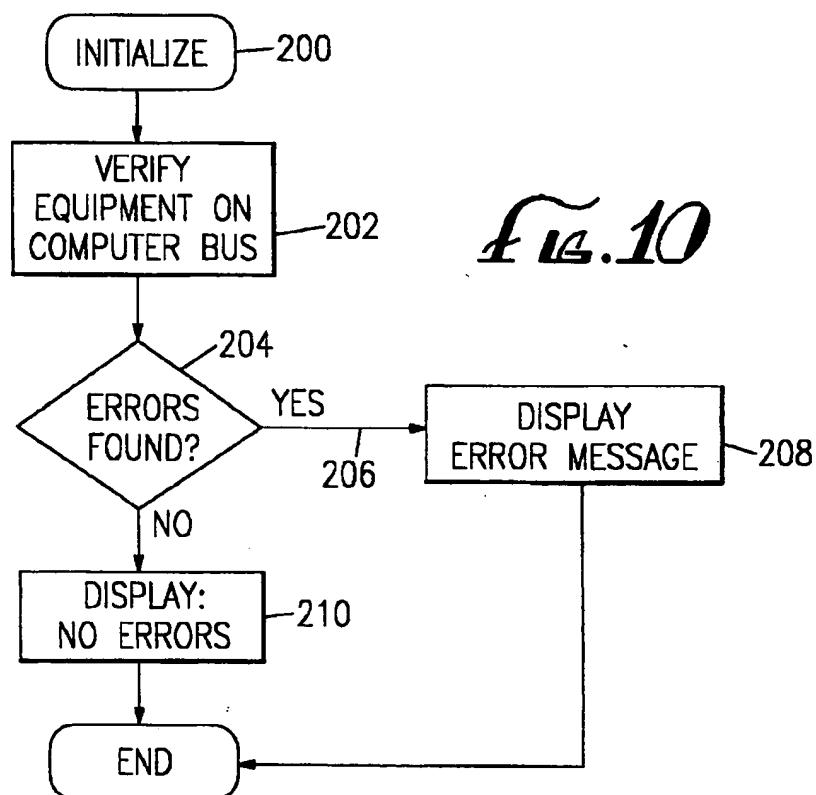
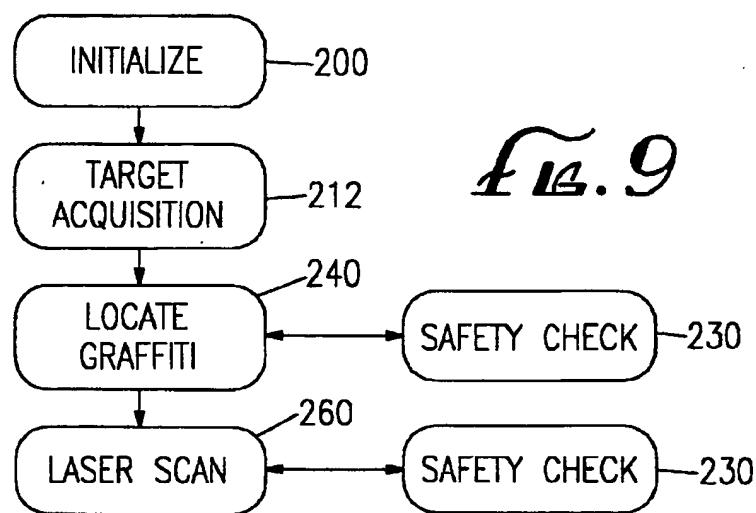
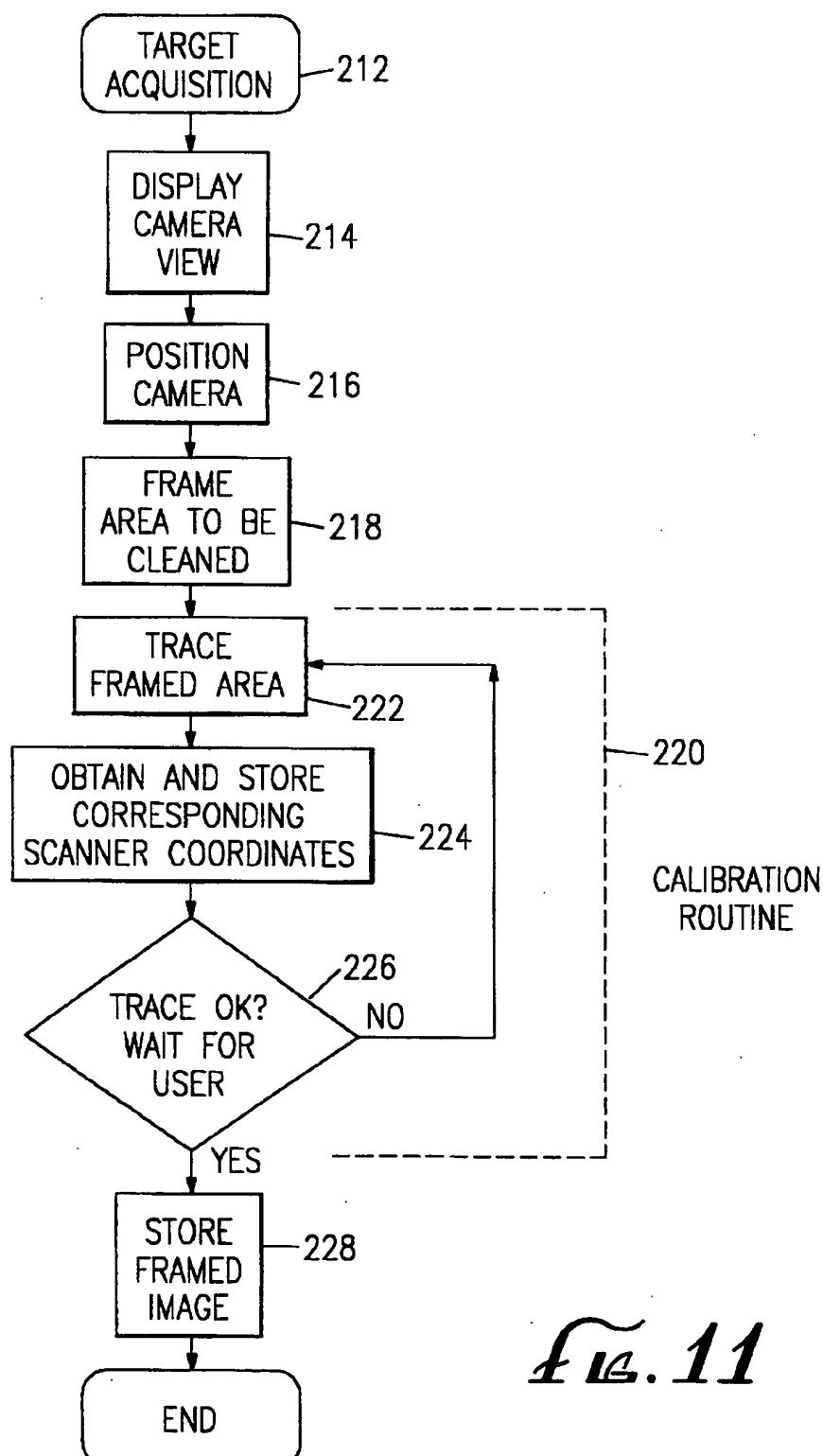
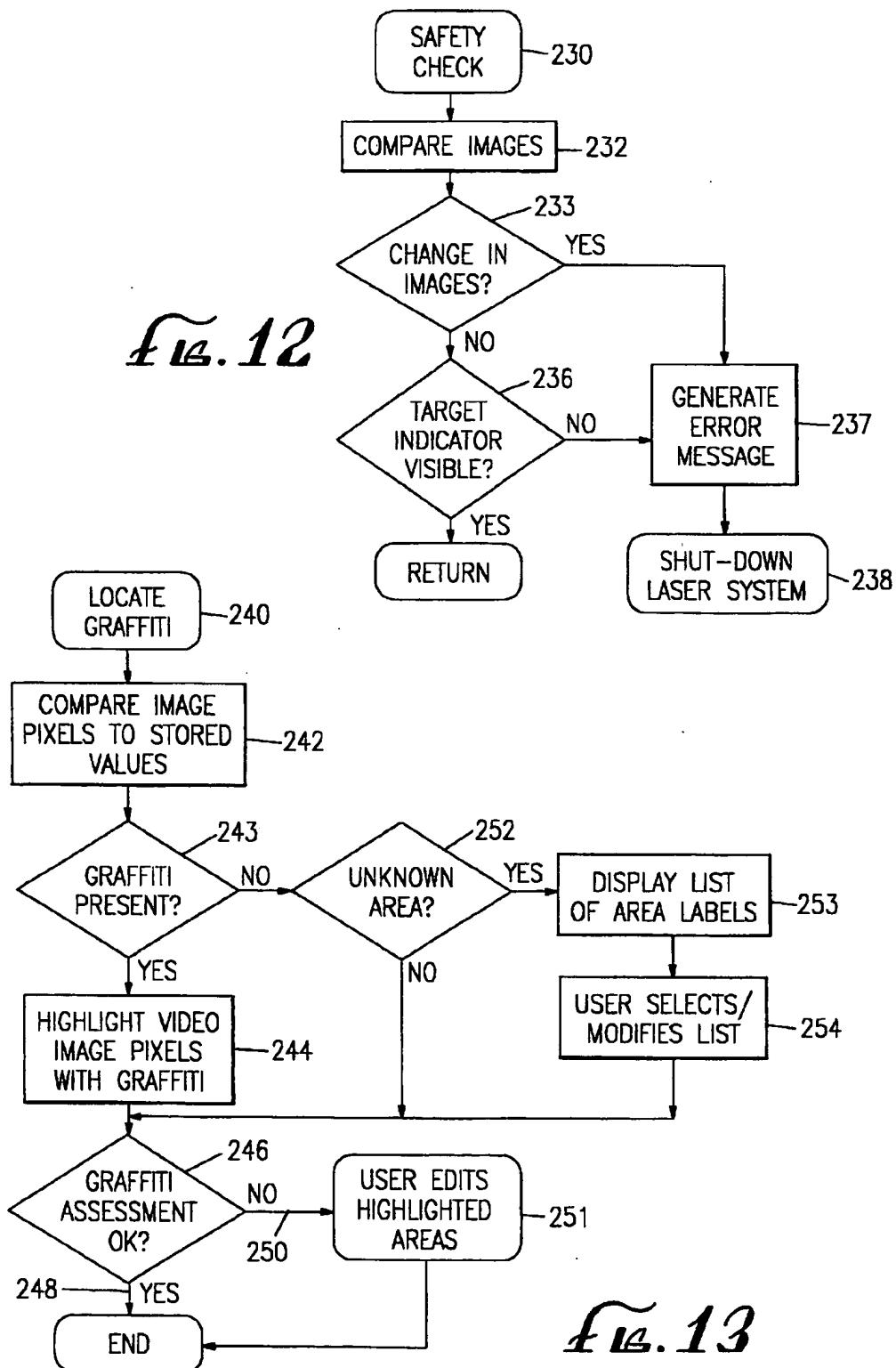


FIG. 8



*FIG. 11*



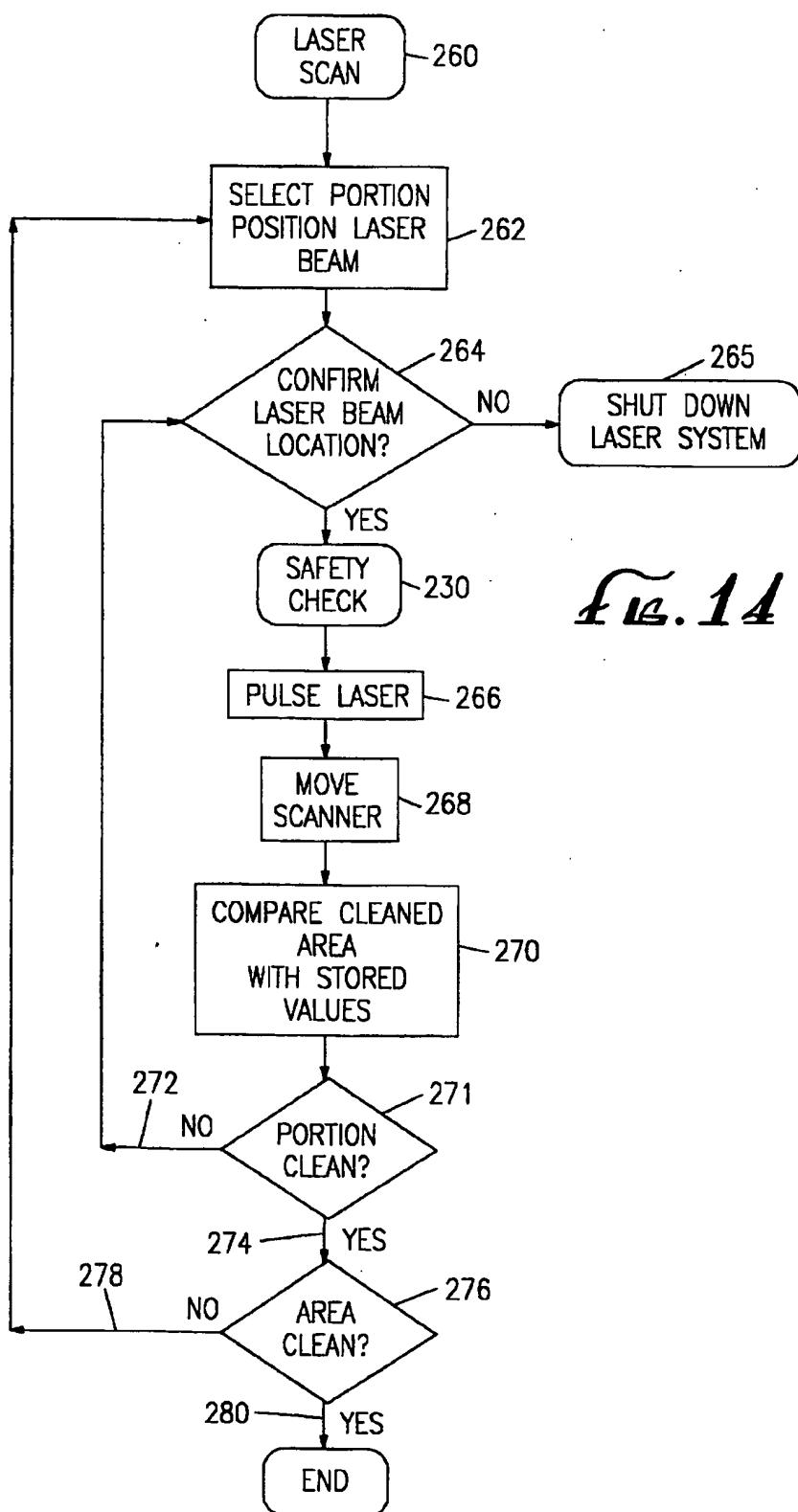


Fig. 14

LASER SYSTEM FOR REMOVAL OF GRAFFITI

BACKGROUND OF THE INVENTION

The display of graffiti on highway and traffic signs has become a common occurrence in many metropolitan areas. Such displays are undesirable as the graffiti can often obscure vital highway and traffic information which may create hazardous conditions and, more importantly, slows down the flow of commerce. The clean-up of graffiti and unwanted paint is very costly, time-consuming and labor-intensive. Conventional ways of cleaning graffiti and other unwanted paint using chemicals or sand blasting are not satisfactory. Chemicals are environmentally unfriendly, may be dangerous to the health of the user, and require storage of large amounts of often dangerous materials. Sandblasting harms the surface, requires the storage of sand, and leaves a pile of sand afterwards. With the limited budgets available to city planners, the graffiti is often left on the highway signs. The motorist is then left to decipher the information underlying the graffiti to avoid getting lost. Periodically, the replacement of the vandalized signs becomes necessary but this solution can be expensive and cost prohibitive for many cities.

One particularly important application is "high intensity" highway signs. These are the "FREEWAY ENTRANCE", "DO NOT ENTER" and "ONE-WAY" signs at every freeway entrance and exit. They contain internal retro-reflectors that make them tremendously bright when observed with automobile headlights. The signs must be placed only a few feet off the ground, so that they are easily observable by drivers. Graffiti destroys their retro-reflectivity and, because they are placed so low, they are easily vandalized. Chemical paint removers must be used when the paint is very fresh, and these removers degrade the signs sufficiently that they may be used only a few times. Sand blasting cannot be used because it destroys the retro-reflection. The only other solution used now is to remove and replace these signs: an expensive proposition.

What is needed is a system to remove graffiti that is environmentally friendly, has very few expendables, is safe for the operator, produces minimum degradation of the surfaces and leaves very little mess at the work-site. At the same time, the cleaning method must be cost-effective. This requires an apparatus with very little set-up and take-down time and minimal labor effort. Ideally, the operator would not have to touch the surfaces at all.

Such a system could be used on highway signs, concrete blocks that surround highways, brick and marble buildings and other structures, stones, trees, and unpainted wooden structures. The system could also be used to remove unwanted paint from selected portions of furniture and other antiques.

With the advent of laser technology, lasers have been used to remove paint from objects such as aircraft or boat hulls. Laser technology systems for such applications have been disclosed that use different sensory devices to detect the amount of paint removed from a given surface. These techniques, while adequate for their intended purpose, preparing the surface of an aircraft or boat for subsequent repainting, do not disclose an adequate system for the restoration of highway signs or other surfaces covered by paint in localized areas.

Hand-held solid-state lasers have been used to clean marble statues and buildings and to remove grime and coal smoke. A Q-switched YAG laser for this use is available for

purchase from Hedge Clemco in England. It uses hand-held fiber delivery system, which is awkward and undesirable where the height of the highway sign may be outside the reach of the operator or where more rapid, automated removal is needed.

5 Pulsed lasers, including Q-switched lasers, have been used to remove portions of integrated circuits in semiconductor devices (laser resistor trimming). Here, the part is usually moved under a fixed laser beam and one or a few 10 blasts are used to remove the unwanted material. There is generally no scanning of the laser beam and there is no interactive control between the position of the unwanted materials and the direction of the laser beam. This application has allowed scientists to understand the process of 15 "ablation" in which the unwanted material is removed so fast that the substrate does not heat up.

Thus, the need exists for a low-cost alternative to conventional graffiti-cleaning techniques in order to restore and extend the life of the highway signs and to remove graffiti 20 easily from bridges, walls and highway abutments. The need also exists for a laser cleaning system that minimizes the damage to the reflective properties of the signs, thereby ensuring their continued service to motorists.

OBJECT AND SUMMARY OF THE INVENTION

It is an object of the present invention to provide a paint removal system for automated removal of undesired paint from a surface.

It is a further object of the present invention to provide an 30 automated system for the automatic identification and removal of graffiti from the surface of a freeway sign.

It is yet another object of the present invention to minimize the loss of the reflective properties of the sign where 35 the graffiti has been removed.

It is another object of the present invention to provide a mobile graffiti removal system that enables the user to remove graffiti from a highway sign or other with a minimal amount of effort.

40 The present invention relates to a mobile laser system for the removal of graffiti from a highway sign or other surface. A laser is used to ablate the surface of a highway sign to remove graffiti with a minimal effect on the underlying highway sign or other surface. In one aspect of the present

45 invention, a laser beam is directed to radiate the surface of the highway sign from an acute angle of incidence to ablate graffiti painted on the surface. The graffiti is burned away from the surface with a minimal effect on the highway sign surface and reflective properties. Chemicals or polish may then be applied to further treat the surface. The detailed 50 aspects of this laser system were developed following extensive research which is disclosed in an AHMCT Research Report entitled "Laser Removal of Graffiti", published on Sep. 22, 1993.

55 The laser is connected in circuit with a computer configured by software to function as a laser control with optical feedback circuit. An optical sensor, preferably a pair of charged coupled device (CCD) video cameras, is positioned to view the highway sign and connected in circuit with the computer. A light source positioned to direct light upon objects within the field of view of the camera is connected in circuit with the computer and cooperates with the optical sensor. A target indicator cooperates with the optical sensor to function as a target acquisition device that identifies the intersection point of the laser with the highway sign.

60 A traveling crane equipped with a boom having a remote end is adapted to deliver a laser pulse from the remote end

to the highway sign. The laser, the light source and optical sensor are preferably located at the base of the crane. The traveling crane is preferably adapted with a laser conduit to direct the laser emissions from the base of the crane to the free end of the boom. The invention is controlled by an operator at the base of the crane with a user interface that includes controls connected in circuit with the computer and controls for operating the boom of the crane to initially position the free end of the boom proximate to the highway sign.

The laser system is initially under the control of the operator who positions the boom proximate to the graffiti on the highway sign either by visually viewing the boom and sign within the operator's line of sight, or preferably by viewing the highway sign from a video monitor included in the user interface that displays the image viewed by the optical sensor.

Once the boom has been positioned, the operator frames a portion of the highway sign to be cleaned on the video display using the user interface. The computer is then actuated by the operator to automatically identify the graffiti within the selected area of the highway sign. The computer locates the graffiti and adjusts a laser scanner at the free end of the boom to direct a laser pulse at an acute angle of incidence to the surface of the sign to be cleaned. The computer pulses the laser to radiate the sign with laser pulses sufficient to remove a layer of graffiti paint. The computer then scans the surface with the optical sensor to compare the area scanned by the laser scanner with a preferred clean characteristic stored in the computer's memory. This procedure is repeated until the computer detects that the graffiti has been removed or the operator determines that the area has been sufficiently cleaned.

The optical sensor is then directed by the operator to the next region to be scanned or, in the case of the operator framing the entire sign, the laser operation is complete. By selectively cleaning only the portions of the sign covered with graffiti, the computer minimizes effects of the laser on the sign. The operator may then use a brush, preferably treated with a chemical cleaner or polish, at the free end of the boom to manually remove any residue remaining on the sign. The laser system will be described in greater detail as follows.

BRIEF DESCRIPTION OF THE DRAWING(S)

FIG. 1 is a perspective view of the laser apparatus of the present invention showing the crane in an operational position;

FIG. 2 is a block diagram of the laser of the present invention;

FIG. 3 is a perspective view of the present invention showing a laser beam path forming a target indicator point;

FIG. 4 is a perspective view of the present invention showing a laser pulse path;

FIG. 5 is a perspective view of the laser scanner of the present invention;

FIG. 6 is a perspective view of the present invention showing the crane in a stand position;

FIG. 7 is cutaway side view of the highway sign of FIG. 4;

FIG. 8 is a block diagram showing the computer and computer peripherals connected to a computer bus;

FIG. 9 is a flow diagram of the laser control with optical feedback software of the present invention;

FIG. 10 is a flow diagram of an initiation routine;

FIG. 11 is a flow diagram of a target acquisition routine; FIG. 12 is a flow diagram of a safety check routine; FIG. 13 is a flow diagram of an identify graffiti routine; and

FIG. 14 is a flow diagram of a laser scan routine.

DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference to FIGS. 2, 3, 4 and 6, the laser system 20 for the removal of graffiti includes generally a laser 22 for ablating paint on the surface of a reflective highway sign 23, a laser scanner 26 configured to deliver a laser emission at any point with a selected area of the highway sign 23, an optical sensor 28 for detecting characteristics of the reflective highway sign and of the graffiti paint, and a computer 32 under the control of an operator 34 and configured by software to function as a laser control and optical feedback circuit.

With continued reference to FIGS. 2, 3, 4 and 6, the present invention is preferably mounted within the flatbed portion of a van 36. An operator user interface (FIG. 8) consists of a conventional computer terminal including a mouse or joystick 40, a keyboard 42 and a video monitor 44. A standard personal computer such as an IBM compatible type, having a central processing unit and memory, includes laser control and optical feedback software stored in memory that, when activated, functions as a laser control and optical feedback circuit for operating the laser system. The computer includes a conventional bus 46 interface in order to send and receive signals to and from the respective peripheral devices.

The laser system (FIGS. 2, 3, 4 and 6) is preferably configured for cleaning a sign located on the passenger side of the van 36 as most highway signs are viewed from the right side of the roadway. The optical sensor 28 is located at the rear end of the passenger side of the van for viewing the front of the highway sign 23 and includes a wide angle video camera 50 and a telephoto video camera 52 connected in circuit with the computer bus 46. A conventional video digitizer 54 connected between the camera and the computer bus 46 converts the camera video signals into a digital form recognizable by the computer 32. The cameras are mounted on a conventional motorized surveillance camera platform 56 connected in circuit with the computer bus. The platform, responsive to signals from the computer, is controlled by the operator using the user interface to position the highway sign within the field of view of the cameras. The platform is preferably mounted on the outside of the van to accommodate the field of view of the cameras. Advantageously, the computer selectively relays the signals representative of the respective camera's field of view to the computer monitor 44 for viewing by the operator to provide visual feedback to the operator adjusting the platform.

Acquisition of the highway sign using the video cameras as a means for digitally imaging the highway sign may be aided with illumination from conventional spotlights 58 and 60. A first light 58 is included positioned in-line with the field of view of the cameras to illuminate the retro-reflective properties of the highway sign. A second light 60 is located at a distance from the camera to illuminate the highway sign in a non-retro-reflecting manner to obtain "matte" reflection. Ambient illumination, if it is available, can be substituted for the second light 60. At different times either ambient light or the second light source 60 may be used to obtain "matte" reflection.

Connected to the computer bus and stored within the van in the preferred embodiment, the laser 22 for ablating the

surface of the highway sign 23 is preferably a conventional Q-switched, Nd:YAG laser which lases in the near infrared wavelength. A conventional configuration for the laser, illustrated in the block diagram of FIG. 2, includes a conventional laser switch circuit 62 that connects with the computer via the bus (FIG. 8) and in response to signals therefrom, pulses the laser on and off. The lasing material is a Neodymium doped YAG crystal 64 that is excited by pulses of light from a flash lamp 66. The YAG crystal 64 is very accurately positioned between two carefully aligned mirrors 68 and 70, with one mirror 68 having transmissive as well as reflective properties, to create a resonant optical cavity 72 or lasing chamber. The flash lamp 66 is used to store energy in the YAG crystal. A Q-switch 74 is positioned within this cavity and connects in circuit to the laser switch circuit 62. The Q-switch operates under the control of the computer to produce very short, intense laser pulses by enhancing the storage and dumping of energy in and out, respectively, of the laser crystal 64. The Q-switch 74 in response to signals from the computer via the laser switch circuit, is operative to direct a laser pulse through the mirror 68 having the transmissive properties. The laser pulse is preferably an ultra short pulsed laser with a peak power of 10 Mega watts lasting about 10 billionths of a second. At this rate, the upper surface layer of graffiti is ablated while minimally affecting the underlying substrate.

A power and cooling unit 76 connects to the laser control circuit and the lasing chamber. The cooling system is a conventional closed water system that draws heat away from the laser crystal and flash lamp and dissipates the heat through a conventional radiator (not shown) contained within the power and cooling unit. All of these components are commercially available. A unit fit for this intended purpose is Model No. DCR-11 sold by Quanta-Ray Spectra-Physics of Mountain View, Calif., U.S.A.

A crane 80, having two vertical legs 82 and 84 mounted at opposite sides of the van proximate the driver's cab section, may be telescopically extended vertically above the roof of the van. The crane includes a boom 86, having a free end 87 telescopically extended horizontally to hang over the roof of the van. The crane legs and boom are extended to position the free end 87 of the boom near a highway sign 23 in an overlying relationship for confronting the front of the sign.

Aligned with the transmissive mirror 68 of the laser is a laser beam conduit 78 for transmitting a laser pulse 79 (FIG. 4) to the laser scanner. In the preferred embodiment, the conduit 75 is formed from carefully aligned optical mirrors 92-93 similar in design to a periscope. The laser conduit is formed within the hollow interior of the crane 80. The crane is movable between an operational position and a storage position. In the stored position (FIG. 6), the legs of the crane are telescopically withdrawn into the roof of the van and the boom is telescopically withdrawn to completely overlie the van roof. During operation, the legs 82 and 84 and boom are telescopically extended using conventional mechanical or hydraulic lifting mechanisms such as means for positioning the free end 87 of the boom.

The laser conduit has several segments 88-90 joined at right angles and includes mirrors 92 and 93 aligned at each orthogonal joint between the segments of the conduit for directing the laser pulse through the bends in the conduit.

In the preferred embodiment, the laser 22 is preferably aligned lengthwise along the length of the van. The first conduit 88 segment connects between the laser output at the transmissive mirror 68 and one of the vertical legs 82 of the

crane. The first mirror 92, having reflective properties on the upper surface at the YAG laser wavelengths and transmissive properties from the lower surface at the HeNe wavelengths, is aligned to reflect the laser pulse from the first segment 88 through an orthogonal bend to the second segment 89 formed within the vertical leg 82 of the crane 80. The second segment 89 of the laser conduit joins the third segment 90 formed within the boom 86 of the crane. The second mirror 93 is positioned at the orthogonal joint between the second and third segments for transferring a laser pulse to the scanner 26 located at the free end 87 of the boom.

With reference to FIG. 3, a target indicator 24 of the preferred embodiment for identifying the intersection point of the laser beam with the highway sign 23 includes a HeNe laser 95, carefully aligned below the first mirror of the laser conduit to produce a visible, low-energy, continuous wave laser beam 96 (FIG. 3) coaxially along the same path of the Q-switched laser pulse. The visible laser beam 96 transmits through the underside of the first conduit mirror 92 and follows the path of the laser pulse through the vertical crane leg, the boom and the scanner to the highway sign. The visible laser 95 is actuated at power up and remains "on" during the operation of the laser system. The visible laser beam delivers a visible red dot 97 at the intersection point where the ablating laser path intersects an object. The red dot functions as a target indicator to identify where the invisible ablating laser pulse will contact the highway sign. The target indicator 24 cooperates with the optical sensors 28 to function as a target acquisition device.

The scanner (FIG. 5), mounted at the free end of the boom, is connected to the computer 32 (FIG. 8) and responsive to signals therefrom to change the laser path to intersect the highway sign at any point along the face of the sign. In the preferred embodiment, the scanner 26 is a conventional angle scanner. The angle scanner includes a mirror 98 at the free end of the boom to intersect the laser path along the boom and reflect the laser energy in a direction orthogonal to the boom. The mirror is connected to the free end of an axle 100 on a galvanometer driven 102 positioned coaxially with the laser beam path at the free end of the boom. The conventional galvanometer driven 102 connects in circuit with the computer bus via a digital to analog converter (not shown) (FIG. 8) and incrementally rotates the mirror 98 on the axle 100 in response to signals from the computer to adjust the radial direction of laser beam from the boom. It will be recognized by those skilled in the art that the scanner operates on the principle of a galvanometer mirror. A device having a 3 msec response time suitable for this purpose is made by General Scanning Corporation, Watertown, Mass.; Model No. GT 325-DT.

The scanner motor 102 is movably coupled to a pair of parallel rails 104 and 105 secured by first and second end plates 106 and 107 at respective opposite ends of the rails and connects to a looped cable 110 which connects to a pair of pulleys at 112 and 113 opposite ends of the rails 104 and 105. The first pulley 112 is freely rotatable and connects to the first end plate 106. The cable projects through apertures 116 in the second end plate 107 and loops around the second pulley 113 which is connected to a vertically aligned axle 118 of a stepper motor 120. The stepper motor 120 is connected in circuit with the computer bus via a digital to analog converter (not shown) (FIG. 8) to function as a servo mechanism (FIG. 5) for laterally moving the scanner along the parallel rails 104 and 105 by incrementally rotating the cable 110 about the pulleys 112 and 113 in response to signals from the computer. Those skilled in the art will appreciate that this scanner configuration uses known principles applicable to x-y plotters.

OPERATION

The laser system 20 is intended for use on site at the location of the highway sign 23. The operator will typically park a converted utility van 36, housing the laser system alongside of the highway sign to be cleaned. Although a precise position is not necessary, the plane formed by the sign should generally intersect the passenger side of the van at the passenger window opposite the driver, thus allowing the driver to visually align the van 36 with the sign 23. Once the van has been aligned the operator parks the vehicle and proceeds to activate the laser system. Upon activation, the computer 32, under the control of software, initiates a conventional initialization and diagnostic routine 200 (FIGS. 9 and 10) to check the computer bus addresses 202 for any flags indicating a failure in the equipment.

If errors are found, at a conditional branch 204, the computer 32 identifies errors 206 and indicates to the operator 34 errors were detected by displaying 208 the appropriate error message on the computer terminal monitor 44 identifying the problems. If no errors are found at the conditional branch 204, the computer displays 210 to the operator that no errors were founded to prepare for scanning of the highway sign.

The computer then begins a target acquisition routine 212. In response to the operator, the computer displays 214 (FIG. 11) the image received from one the cameras. The operator uses the joystick or mouse to control the camera platform to rotate 216 the cameras to place the highway sign within the field of view of the camera. In the preferred embodiment, the crane 80 (FIG. 6) is then actuated by the operator 34, raising the legs and extending the boom, to position the laser scanner 26 in a confronting overlying position with the face of the highway sign (FIG. 1). Once the scanner has initially been positioned the operator may view images of the sign without the on-axis light source 58, to check the ambient lighting. If additional lighting is needed, the off-axis, supplemental light source 60 is manually positioned by the operator to illuminate the highway sign. After the lighting has been checked the operator then, viewing the sign from the monitor, frames 218 (FIG. 11) the portion of the highway sign to be cleaned with the mouse or joystick using conventional point and click editing algorithms such as provided by Microsoft Windows®. Using the red dot 97 (FIG. 3) to indicate the intersection point of the laser pulse path with the highway sign, the coordinates of the framed portion of the highway sign displayed on the monitor are calibrated 220 (FIG. 11) by the computer with the scanner. The red dot 97 when displayed within the field of view of the camera is visually recognizable by the computer. The computer uses the position of the red dot as a reference to perform conventional feedback algorithms, such as hi-low or fuzzy logic, to signal the laser scanner to trace 222 the red dot along the border of the framed area. The corresponding laser scanner coordinates are stored 224 by the computer. Once the laser scanner and cameras have been calibrated, the operator is prompted 226 to ensure the area has been correctly identified. If the operator verifies the computer has correctly identified the framed area, the digital image of the framed area is stored 228, otherwise the computer repeats the calibration steps 220.

Once the image is stored 228, the computer continuously uses the digital image to periodically perform a safety routine 230 (FIG. 12) that compares 232 the stored image with a live image to check for image changes 233 to ensure no objects or people obstruct the laser path. The safety routine 230 also continuously checks 234 for the presence of

the red dot in the live image. Upon detecting the absence of the red dot or a change in the live image with stored digital image, the computer generates 236 an error message on the monitor 237 and shuts down 238 the laser system. The operator then can manually identify the problem, correct any obstruction and restart the system.

Upon completing the target acquisition routine 212, the computer performs a locate graffiti routine 240 using the video cameras. The locate graffiti routine uses conventional optical recognition algorithms using stored values relating to the reflective characteristics of the retro-reflective highway surface and the graffiti. In the preferred embodiment (FIG. 13), the computer compares 242 each pixel of the bit-mapped digital image of the area framed by the operator with the stored reflective characteristics and checks for the presence of graffiti 243. The computer then graphically highlights 244 the regions containing graffiti on the monitor and prompts 246 the operator to verify 248 or modify 250 the computer's identification of the graffiti. If needed, the operator can add or delete highlighted portions using the mouse or joystick to move a cursor on the monitor using the conventional point and click editing algorithms 251 to add to or delete from the highlighted areas. If the computer finds an area having unknown characteristics, the computer may also prompt 252 the operator to identify the unknown area, such as a hole in the sign. The operator may view and assess the unknown area to determine if the point contains graffiti or holes. In one preferred embodiment, the computer stores and displays 253 a modifiable list of unknown area types. The operator then selects 254 a label from the list to identify the region to the computer, or adds a new label to identify this characteristic. Unless the unknown area is labeled as graffiti, the computer does not highlight the unknown area.

Satisfied with the highlighted display of graffiti, the operator then signals the computer 248 to begin a laser scan routine 260 that automatically scans the graffiti-covered portions with the ablating laser. The laser scan routine 260 positions the laser beam 262 at a point convenient to begin scanning of the graffiti, such as the upper left point in the highlighted regions. The computer confirms 264 the location of the laser by using the cameras to locate the position of the red dot. If the calibration is off, the computer shuts down the system 265. Upon confirming the calibration, the safety check loop 230 is initiated. The computer then signals 266 the laser switch circuit to begin pulsing the Q-switched laser while also signaling 268 the scanner to scan the laser intersection point across a computer-selected portion of the highlighted graffiti. The computer, upon completing a scan, checks the image of the area scanned using the telephoto camera and determines 270 whether the area has been cleaned using conventional optical recognition algorithms such as comparing the image with the non-highlighted regions of the prior scanned image or with stored predetermined values. If the computer comparison result 271 indicates graffiti remains 272, then the scan is repeated.

Once the computer has determined that the scanned portion is clean 274, it checks to determine if all highlighted portions have been scanned 276. If not, it moves on to the next computer-selected portion 278 and performs the same scan routine. This routine is repeated until the entire highlighted area has been cleaned of graffiti 280.

In the preferred embodiment, the computer-selected portions are rows or columns of the graffiti-covered highlighted area. The width of each column or row corresponds to the width of the laser pulse, about 3 cm². In the preferred embodiment, the laser pulse width must correspond to the resolution width of the pixels in the telephoto camera.

The laser is pulsed at a preferred rate of 50 pulses per second to handle the program routine timing. The scanner motor has a has a preferred response rate of about 3 milli-seconds. The laser pulse rate provides ample time between pulses for the computer to complete movement of the scanner 268 and execute the safety routine 230 before each subsequent laser pulse is transmitted 266.

Even using a discrete 10 billionths of a second pulse rate to minimize the laser effects on the sign, the laser will reduce the retro-reflective properties of the highway sign 24 formed from beads of glass 302 when viewed at the angle of impact 300 (FIG. 7). Therefore, the angle of impact must not be within range of views 304 and 306 visible by motorists. The boom is preferably adjusted to confront the highway sign from an overlying position, forming an acute angle 300 of no more than 45° between the laser beam and the plane of the highway sign. This position ensures that the angle of impact is outside the angles 308 and 310 viewed by motorists.

Upon completion of the laser cleaning operation, the operator 34 may then use a brush, optionally treated with a chemical solvent or polish, to clean the surface of any remaining graffiti and polish the surface to further restore the retro-reflective properties. Commercially available products fit for this purpose are Bon Ami™ or So-Safe™. Following cleaning with a protective spray applied to the sign, a spray such as Armour All™ may be used to resolve the reflective properties. Also, a spray coating to protect against further vandalism could be applied.

In an alternatively preferred embodiment, the laser scanner may comprise a conventional position scanner to accommodate a fiber optic conduit. The fiber optic conduit eliminates the need for the precisely aligned mirrors and could accommodate alternative boom designs with increased mobility such as a modified "cherry picker", which is used to hold a person at the free-end of the boom. The computer would control the laser and scanner in a similar manner. Those skilled in the art will also appreciate that the laser control and optical feedback circuit could also be configured on a solid state integrated circuit, such as an Application Specific Integrated Circuit (ASIC).

It will be appreciated that the present invention may also be used on surfaces such as cement or wood to remove graffiti paint. However, when used on these surfaces, the operator would use the joystick or mouse to highlight the graffiti areas. The computer would then locate the coordinates of the area highlighted using the target acquisition device in the same steps following framing of an area. Then pulses from the laser while scanning the region ablate the graffiti from the surface. Upon completing a scan, the operator would then again visually inspect the region using the video monitor and highlight additional portions if further scanning by the laser system is required.

While a particular form of the invention has been illustrated and described, it will be apparent that various modifications can be made without departing from the spirit and scope of the invention. Accordingly, it is not intended that the invention be limited, except by the claims appended herein.

What is claimed is:

1. A mobile laser apparatus for the removal of graffiti from a highway sign comprising:

an ablating laser being energized such that ablating laser emissions are generated to ablate the surface of said highway sign;

an optical sensor movably positioned to view said highway sign to generate optical sensor signals representative of the surface of said highway sign;

a laser scanner movably positioned proximate to said highway sign to direct said ablating laser emissions at the surface of said highway sign; conduit means for transmitting said ablating laser emissions from said ablating laser to said laser scanner; a target indicator in alignment with said laser scanner to identify an intersection point of said ablating laser emissions with said highway sign;

a control and feedback circuit connected in circuit with said ablating laser, optical sensor and laser scanner such that said control and feedback circuit, in response to said optical sensor signals, controls said ablating laser and said laser scanner to direct laser emissions at graffiti on the surface of the highway sign causing ablation of said graffiti;

said target indicator includes a visible laser being mounted to deliver visible laser emissions coaxial with said ablating laser emissions from said laser scanner to produce a visible reference point on said highway sign indicating said intersection point;

said optical sensor in response to sensing said visual laser emissions, generates a target signal representative of the location of said intersection point, and said control and feedback circuit, in response to said target signal, identifies the position of said intersection point on the surface of said highway sign;

said feedback and control circuit includes safety means for shutting down said laser apparatus in response to an unsafe condition; and

said safety means includes a memory for storing a reference image and shuts down said ablating laser in response to detecting differences between said optical sensor signal and said reference image such that an object moving in front of the highway sign may be detected.

2. A mobile laser apparatus for the removal of graffiti from a highway sign comprising:

an ablating laser being energized such that ablating laser emissions are generated to ablate the surface of said highway sign;

an optical sensor movably positioned to view said highway sign to generate optical sensor signals representative of the surface of said highway sign;

a laser scanner movably positioned proximate to said highway sign to direct said ablating laser emissions at the surface of said highway sign;

conduit means for transmitting said ablating laser emissions from said ablating laser to said laser scanner; a target indicator in alignment with said laser scanner to identify an intersection point of said ablating laser emissions with said highway sign;

a control and feedback circuit connected in circuit with said ablating laser, optical sensor and laser scanner such that said control and feedback circuit, in response to said optical sensor signals, controls said ablating laser and said laser scanner to direct laser emissions at graffiti on the surface of the highway sign causing ablation of said graffiti;

said target indicator includes a visible laser being mounted to deliver visible laser emissions coaxial with said ablating laser emissions from said laser scanner to produce a visible reference point on said highway sign indicating said intersection point;

said optical sensor in response to sensing said visual laser emissions, generates a target signal representative of

11

the location of said intersection point, and said control and feedback circuit, in response to said target signal, identifies the position of said intersection point on the surface of said highway sign; and
 said control and feedback circuit includes reference image means for retrieving and storing an optical sensor signal representative of a portion of said highway sign to be scanned by said laser scanner.

3. The laser apparatus of claim 2 wherein said control and feedback circuit includes means for recognizing graffiti within said reference image.

4. The laser apparatus of claim 3 wherein said control and feedback circuit, upon recognizing graffiti, signals said laser scanner to direct said laser emissions at said graffiti and signals said ablating laser to generate ablating laser emissions to ablate said graffiti such that scanning of the graffiti within said reference image thereby removes graffiti from the surface of said highway sign.

5. The laser apparatus of claim 4 wherein said scanner is positioned to direct laser emissions at an acute angle no more than 45 degrees to a plane defined by the surface of said highway sign such that the laser grazes the surface of said highway sign.

6. The laser apparatus of claim 2 wherein said control and feedback circuit includes calibration means for adjusting laser scanner coordinates to correspond with coordinates of said portion of said highway sign such that said control and feedback circuit can signal said laser scanner to move said intersection point to any coordinate within said portion.

7. A mobile laser apparatus for the removal of paint from a surface comprising:

an ablating laser to generate ablating laser emissions having a predetermined pulse and wavelength to ablate paint from a surface.

a laser scanner movably positioned proximate to said surface to direct said ablating laser emissions at least one intersection point on said surface;

means for transmitting said laser emissions from said ablating laser to said laser scanner;

an optical sensor movably positioned to view said surface to generate optical sensor signals representative of said surface;

a target indicator in alignment with said laser scanner to identify said intersection point between said laser emissions and said surface; and

5

15

20

25

30

35

40

45

12

a control and feedback circuit connected in circuit to said ablating laser, said laser scanner and said optical sensor and including a user interface having a display and an editing device, means for calibrating said laser scanner to scan paint on said surface and means for controlling said ablating laser and said laser scanner to ablate said paint on said surface such that said control and feedback circuit in response to said optical sensor signals from said optical sensor displays an image representative of said surface on said display to thereby allow a user operating said editing device to manually identify said paint on said surface whereby said calibrating means and said control means cooperate to position said laser scanner to automatically remove paint from said surface.

8. The mobile laser apparatus of claim 7 wherein said ablating laser is a ablating laser having generally a 10 billionths of a second pulse rate.

9. The mobile laser apparatus of claim 7 wherein said mobile laser apparatus includes:

a vehicle housing said ablating laser, laser scanner, said optical sensor and said control and feedback circuit to provide mobility such that an operator drives said vehicle to a remote surface; and
 said vehicle includes a crane having an extendable boom connected to said laser scanner at a free end such that, upon positioning said Vehicle alongside said remote surface, said extendable boom positions said laser scanner proximate to said surface.

10. A mobile laser apparatus for the removal of paint from a sign comprising:

an ablating laser;
 an optical sensor movably positioned to view said sign;
 a laser scanner movably positioned proximate to said sign;
 a laser transmission conduit connected between said ablating laser and said laser scanner;
 a target indicator aligned with said laser scanner;
 said optical sensor connected in spaced apart relation with said laser scanner and independently movable relative to said laser scanner; and
 a control and feedback circuit connected to said ablating laser, optical sensor and laser scanner.

* * * * *



US 20030043964A1

(19) United States

(12) Patent Application Publication (10) Pub. No.: US 2003/0043964 A1
Sorenson (43) Pub. Date: Mar 6, 2003

(54) INSPECTION SYSTEM AND METHOD

(75) Inventor: Michael R. Sorenson, Ashland, OR
(US)

Correspondence Address:
WHITE & CASE LLP
PATENT DEPARTMENT
1155 AVENUE OF THE AMERICAS
NEW YORK, NY 10036 (US)

(73) Assignee: JetRay Corporation

(21) Appl. No.: 09/944,693

(22) Filed: Aug 31, 2001

Publication Classification

(51) Int. Cl.⁷ G01B 15/06; G01N 23/06

(52) U.S. Cl. 378/58; 378/51

(57) ABSTRACT

An inspection system utilized to inspect a structure for particularities, including defects, includes a first gantry with a detector inspection device that is placed in a known position on one side of the structure, and a second gantry with a source inspection device that is placed on the other side of the structure. In an embodiment, the detector inspection device is an x-ray detector inspection device and the source inspection device is an x-ray source inspection device. The movement of the first and second gantries is controlled by a gantry control system. A data acquisition system controls the data, e.g., image, collection process. During the data collection process, the relative positions of the source and detector inspection devices are initialized. The detector and source inspection devices are then moved in synchronized motion to each data collection position, such that the relative alignment of the inspection devices is maintained. In an embodiment, a programmed inspection sequence directs data collection positioning for automated coverage of the structure. In an alternative embodiment, manual positioning may be utilized. The detector and source inspection devices collect data, e.g., images, of the structure at each data collection position.

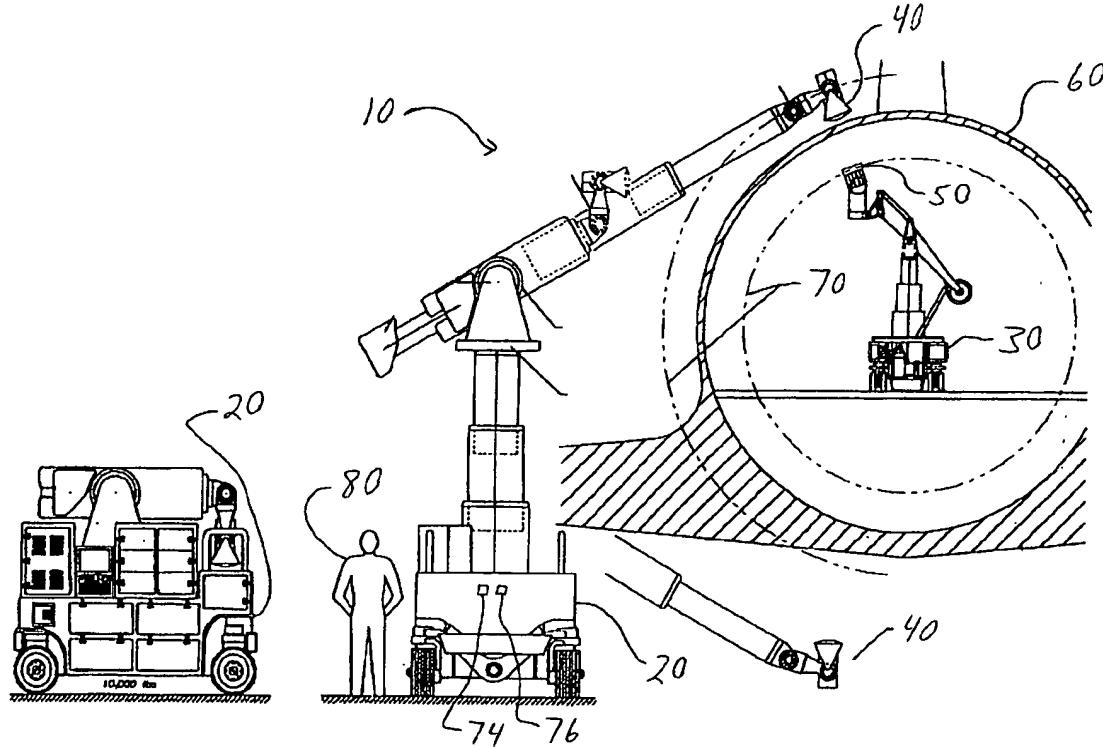


FIGURE 1

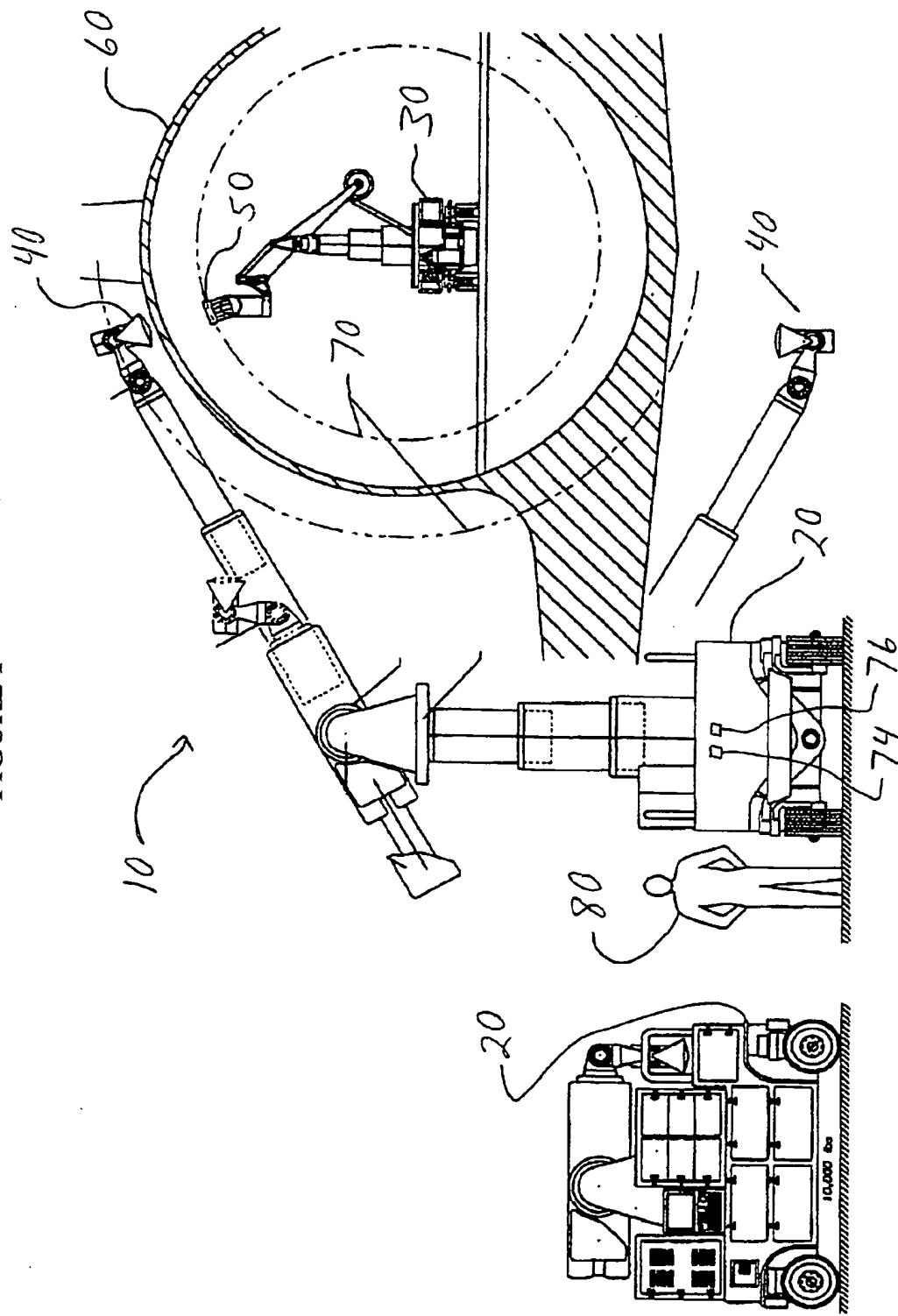


FIGURE 2

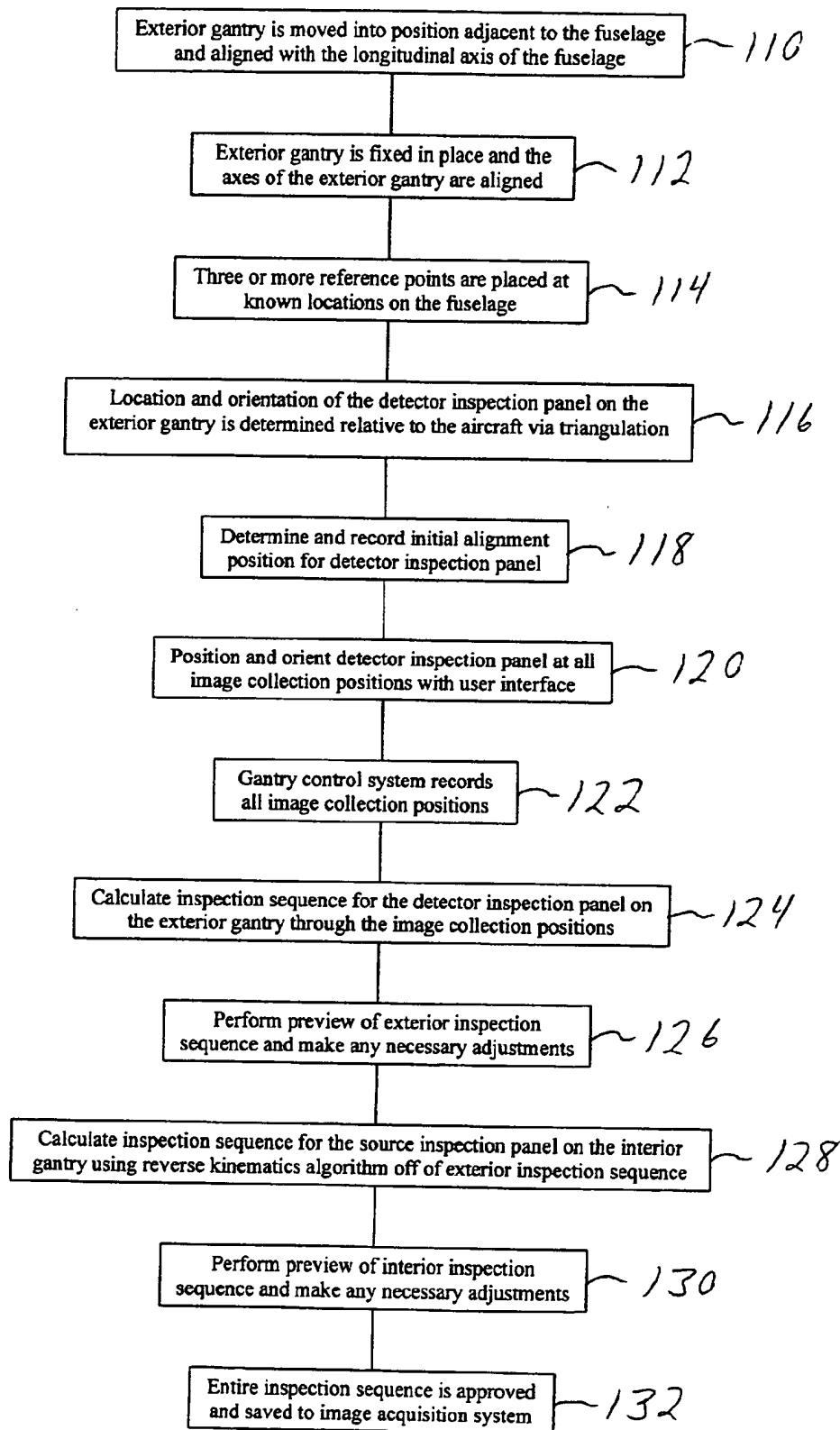
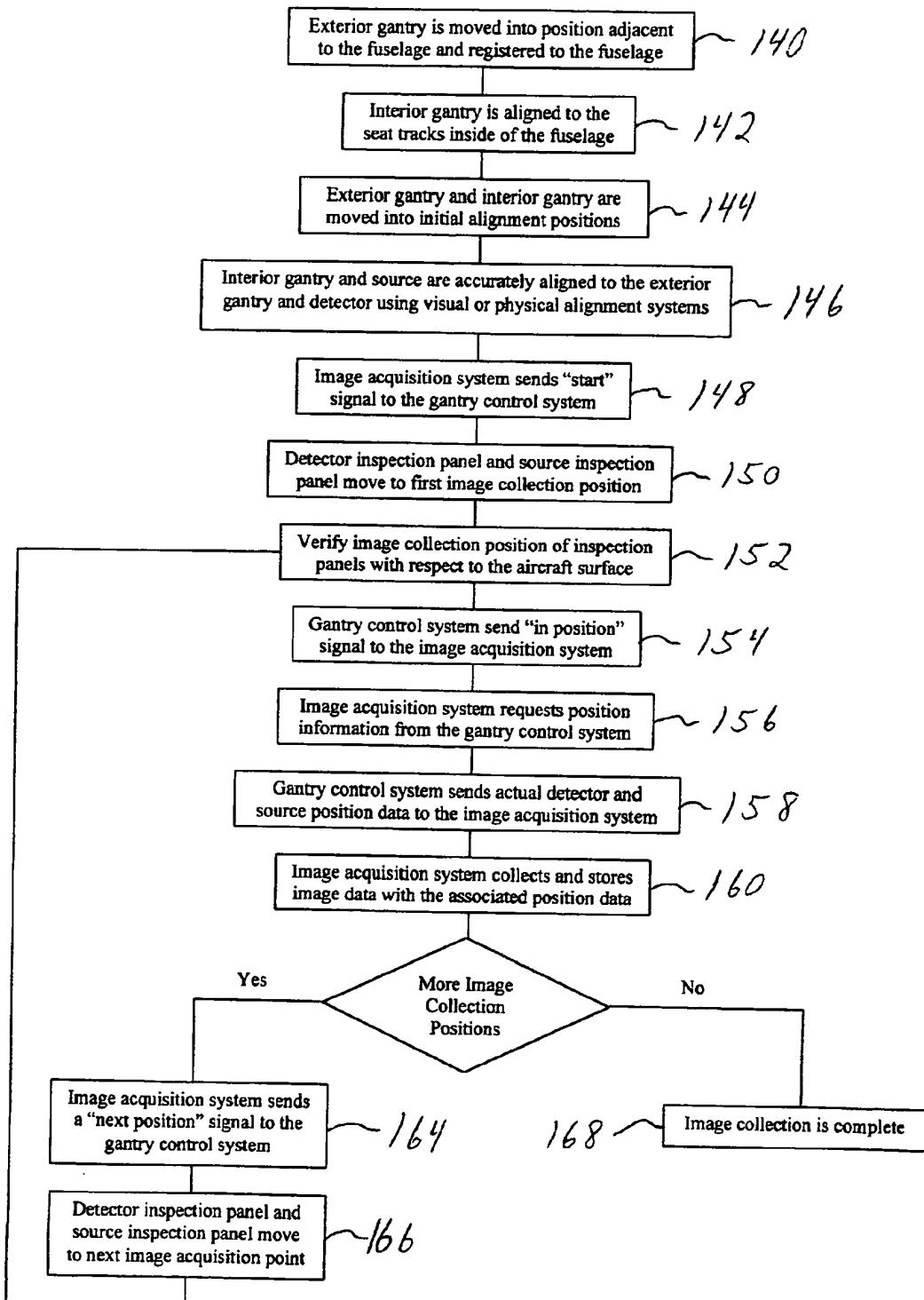


FIGURE 3

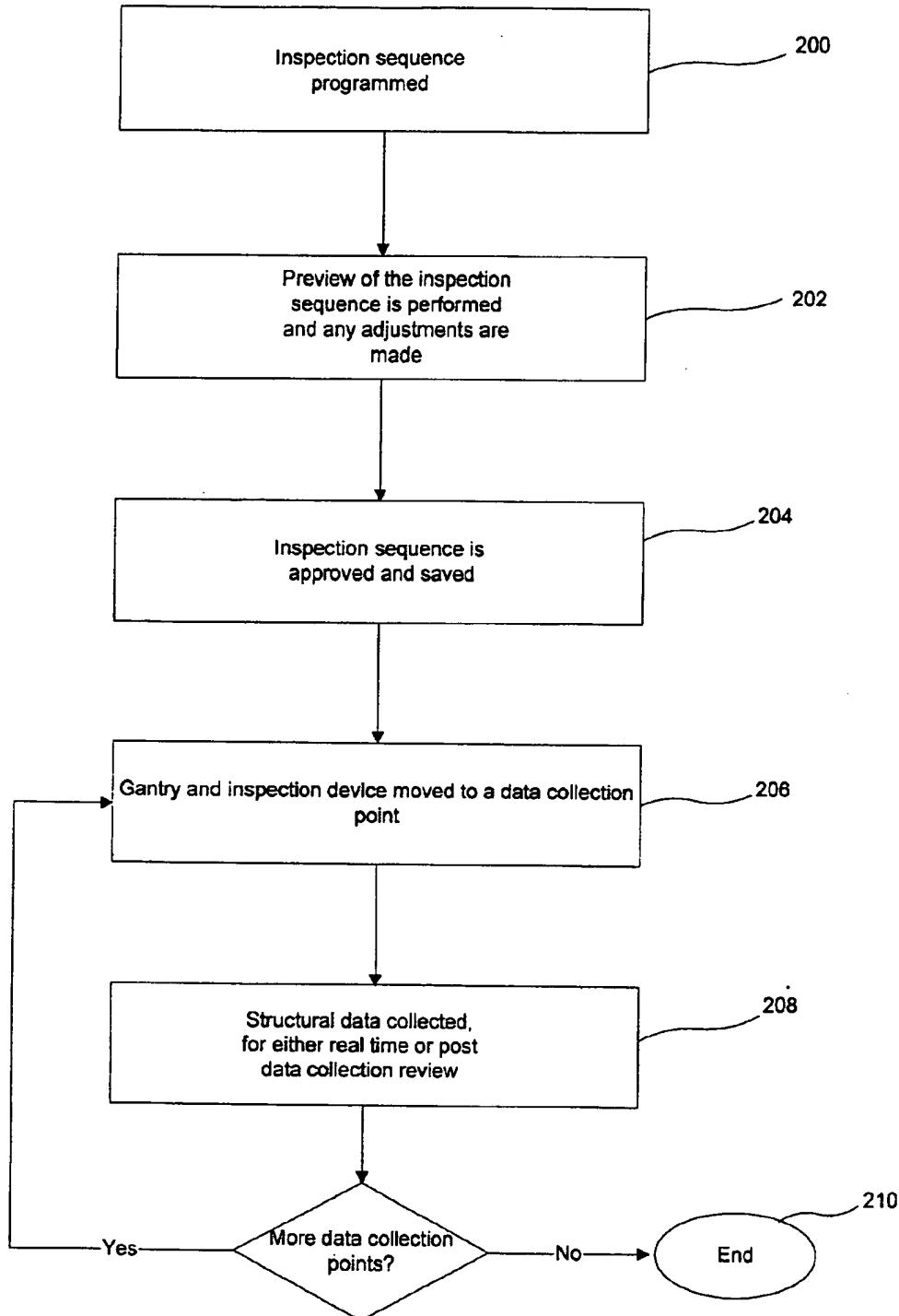


FIGURE 4

INSPECTION SYSTEM AND METHOD

FIELD OF THE INVENTION

[0001] This invention relates generally to inspection methods for identifying structural particularities and, more particularly, to an inspection method for identifying defects, including cracks and corrosion, in aircraft.

BACKGROUND

[0002] "Aging aircraft" is a Federal Aviation Administration (FAA) classification for a commercial aircraft with over 36,000 cycles on its airframe, or 15 years of service life, or a combination of cycles and years of service life. A cycle comprises a takeoff and landing. Worldwide, there are thousands of aircraft in the "aging aircraft" category.

[0003] The FAA requires that an aging aircraft be inspected for cracks and corrosion at regular intervals. Current known inspection techniques use visual inspection. To prepare for a visual inspection, the interior of the fuselage must be stripped of seats, bins, galleys, panels, and insulation. Further, the visual inspection process itself typically takes several personnel ten days or more to complete. Moreover, it has been found that a crack may not be identified with a visual inspection until it reaches a length of two to four inches. Additionally, cracks and corrosion on the interior layers or frame members cannot be seen at all using visual inspection. Overall, the visual inspection technique is slow, laborious, damaging to aircraft materials, and less than optimally effective for crack and corrosion detection.

[0004] Alternative non-invasive inspection techniques, such as x-ray inspection, would provide superior detection of cracks and corrosion in an aircraft fuselage. Additionally, the aircraft's panels and insulation would not have to be removed. However, there is currently no practical way of performing a comprehensive x-ray inspection of an aircraft. To obtain an x-ray image through a fuselage (or wing) requires that an x-ray source or emitter and an x-ray detector, located inside and outside of the fuselage respectively, be positioned with respect to each other at the time that the images are obtained.

[0005] Accordingly, those skilled in the art have long recognized the need for a new method of efficiently performing an inspection of an aircraft. The present invention clearly fulfills these and other needs by providing the means to perform an efficient and non-invasive inspection, reducing the time and cost required to prepare an aircraft for inspection, reducing the time to perform the inspection, and increasing the effectiveness and quality of the inspection. The structure and method of the present invention may also be used to identify components, or particularities, of any structure, including, for example, ships and buildings.

SUMMARY

[0006] Briefly, and in general terms, the present invention resolves the above and other problems by providing an inspection method for inspecting a structure and identifying particularities, such as defects, in the structure. The inspection method includes: positioning two inspection devices at a pre-determined distance from each other, one of the inspection devices inside of the structure and the other inspection device outside of the structure, wherein the two

inspection devices comprise a detector inspection device and a source inspection device; collecting data, such as images, of a portion of the structure located between the source and the detector; moving the inspection devices on the inside and the outside of subsequent portions of the structure to be inspected while maintaining an approximate distance between the inspection devices without reliance on a physical or optical link between the inspection devices; and collecting data of the additional portions of the structure located between the inspection devices.

[0007] In accordance with an aspect of the present invention, the inspection devices are automatically moved to each portion of the structure to be inspected according to an inspection sequence that controls the movement of the inspection devices along the structure. In an embodiment, the inspection sequence is a programmed inspection sequence. The programmed inspection sequence that controls movement of the inspection devices along the structure may be produced at some time prior to the inspection by an operator moving one or both of the inspection devices through data collection positions and programming the data collection positions into the inspection sequence. In an embodiment, during the creation of the programmed inspection sequence, sections of the inspection sequence that correspond to similar or substantially similar portions of the structure are repeated within the inspection sequence during the programming, thereby, among other things, simplifying the programming of the inspection sequence.

[0008] In an embodiment, the programmed inspection sequence that controls movement of the inspection devices along the structure is produced from surface data generated from visual surveying equipment. In another embodiment, the programmed inspection sequence is produced from surface model data derived from Computer Assisted Design (CAD) data. In yet another embodiment, the source inspection device and the detector inspection device are manually moved to each portion of the structure to be inspected.

[0009] In accordance with another aspect of the present invention, the source inspection device comprises an x-ray source and the detector inspection device comprises an x-ray detector. In an embodiment, the source is mounted on a first gantry and the detector is mounted on a second gantry. A gantry is a motion control device that allows positioning of an inspection device at a desired position. A gantry consists of two or more linked mechanical structures, the relative positions of which are controlled by actuators. A construction crane or a "cherry picker" are examples of gantries. The first and second gantries are synchronized to move in coordinated motion with each other under the direction of a gantry control system. Alternatively, it is not required that both gantries move in strict synchronization; it is only required that the inspection devices stop at prescribed relative positions so that satisfactory data, such as images, can be acquired. Either of these types of relative motions will be referred to herein as synchronized motion.

[0010] In another embodiment, one inspection device is mounted on an interior gantry that utilizes a track assembly and the other inspection device is mounted on an exterior gantry that utilizes a rover vehicle. A rover vehicle is a ground-based vehicle that carries the external gantry from point to point. In an embodiment, the rover has four-wheel independent steering to increase maneuverability.

[0011] In accordance with another aspect of the present invention, the inspection devices are initialized at home positions that allow for direct or visual contact between the inspection devices. In an embodiment, the task of initializing a gantry or inspection device consists of moving the inspection device to a known location and entering into the motion control system the coordinates of the known location either in the gantry or the coordinate system of the structure to be inspected, e.g., the aircraft coordinate system. In another embodiment, the task of initializing a gantry or inspection device consists of moving the gantry to a known internal configuration, or home position, and entering into the motion control system the gantry coordinate system values for that position. In yet another embodiment, the task of initializing a gantry or inspection device consists of moving two inspection devices to specific locations relative to each other and entering into the motion control system the relative coordinates of one or both inspection devices or gantries.

[0012] In an embodiment, the structure that the inspection method is designed to inspect comprises an aircraft. Additionally, in an embodiment the particularities that the inspection method identifies comprise cracks and corrosion. In an alternative embodiment, the structure that the inspection method is used to inspect comprises any structure, including, but not limited to, a building or a ship.

[0013] Another embodiment of the present invention is also directed towards an inspection method for identifying particularities, such as defects, in a structure. The inspection method includes: placing a first gantry having an attached inspection device in a known position located outside of the structure; placing a second gantry having an attached inspection device inside of the structure, wherein the inspection devices comprise a detector inspection device and a source inspection device; initializing the relative positions of the inspection devices; moving the inspection devices in a coordinated manner to each data, e.g., image, collection position according to an inspection sequence that controls movement of the inspection devices along the structure while maintaining the relative alignment of the inspection devices; and collecting data, e.g., images, of the structure at each data collection position.

[0014] In accordance with an aspect of the present invention, the motion of a gantry can be mathematically derived from the desired motion of the respective inspection device, where the desired motion of the inspection device is characterized with respect to an inspection device based coordinate system. The coordinate axis system of the inspection device is defined as a set of artificial axes. The term artificial is used to denote the fact that the inspection device's coordinate axes typically have no one corresponding gantry motion directly associated with them. Generally, to move an inspection device along one of its artificial axes typically requires that two or more gantry axes be actuated.

[0015] In an embodiment, the artificial axes are correlated, or otherwise registered, to the geometry of the structure to be inspected, e.g., the aircraft geometry. The artificial axes allow an operator to move the inspection device in its coordinate system, thereby simplifying the operator's task of maintaining the inspection device in a constant orientation relative to the surface of the structure to be inspected, e.g., parallel or perpendicular to the aircraft fuselage, at all times

as the inspection device is moved along the structure. Without the use of the artificial axes of the inspection device, the operator would be required to characterize the desired motion of the inspection device with respect to the gantry axes, and manually manipulate several gantry axes at the same time while simultaneously attempting to follow the changing geometry of the structure to be inspected, e.g., the aircraft.

[0016] In an embodiment, once the position of one of the inspection devices is determined, a corresponding position for the second inspection device is obtained. The position of the second inspection device can be an offset from the first inspection device position. In an embodiment, the offset is the distance between the inspection devices along an artificial axis, such as the normal axis to the first inspection device's front surface. The required motion of the gantry supporting the second inspection device to move the second inspection device to a designated position can be mathematically derived by a process of reverse kinematics.

[0017] Reverse kinematics utilizes the gantry geometry, the location and orientation of the inspection device on the gantry, and the desired position of the inspection device to adjust the gantry actuators appropriately. In an embodiment, reverse kinematics can be utilized to generate a set of motions for a second gantry that will achieve a sequence of data collection positions for the second inspection device corresponding to a programmed sequence of data collection positions for the first inspection device. In an embodiment, reverse kinematics may be utilized to derive a set of interior gantry motions that will achieve a sequence of image collection positions for an x-ray source inspection device corresponding to a programmed sequence of image collection positions for an x-ray detector inspection device, while maintaining the relative alignment and synchronized motion of the inspection devices. In an alternative embodiment, reverse kinematics can be utilized to derive a single position at a time for the second, e.g., source or interior, inspection device, and then repeated to retain synchronization of the second inspection device with the first, e.g., detector or exterior, inspection device for each new position of the first inspection device.

[0018] In an embodiment, the data collection, such as imaging, of each portion of the structure under inspection is performed when the motions of the gantries are intermittently stopped.

[0019] Another embodiment of the present invention is a method for creating an inspection sequence to be used in inspecting a structure for particularities, such as defects. This method includes: aligning an exterior gantry having an inspection device with the structure to be inspected; initializing all axes of the exterior gantry; creating at least three reference points at known locations on the structure; determining the location and orientation of the inspection device relative to the structure via triangulation to the reference points; determining data, e.g., image, collection positions for the inspection device of the exterior gantry; positioning and orienting the attached inspection device with respect to the structure at the data collection positions and recording the data collection positions; and, using reverse kinematics to derive a set of interior gantry motions that will achieve a sequence of data collection positions for the inspection device on the interior gantry corresponding to a programmed

sequence of image collection positions for the inspection device on the exterior gantry, while maintaining the relative alignment and synchronized motion of the inspection devices.

[0020] In accordance with an aspect of the present invention, the inspection sequence is programmed to automatically move the inspection devices to each data, e.g., image, collection position on the structure. In an embodiment, the inspection device of the exterior gantry comprises an x-ray detector and the inspection device of the interior gantry comprises an x-ray source. In an embodiment, the exterior gantry is a master system and the interior gantry is a slave system.

[0021] Another embodiment of the present invention is an inspection method for identifying particularities, such as defects, in a structure. The inspection method includes: locating an exterior rover gantry having a detector inspection device to a pre-determined home position outside the structure and correlating, or registering, the gantry to the structure; mounting an interior rail gantry having an x-ray source inspection device onto alignment tracks at a pre-determined home position located inside the structure; aligning the detector inspection device of the exterior gantry with the x-ray source inspection device of the interior gantry through physical or optical or other applicable means; implementing an inspection sequence to move the detector inspection device and the source inspection device to each image collection position; and obtaining an x-ray image at each image collection position with the inspection devices. In an embodiment, the inspection sequence is a programmed inspection sequence for automatically moving the detector and source inspection devices to each image collection position. In an embodiment, the inspection method can utilize an alignment system for referencing the structure, including, but not limited to a target alignment system, a laser alignment system, a radio frequency alignment system, a physical alignment systems, or an optical alignment system. Other known alignment techniques may also be utilized.

[0022] Another embodiment of the present invention is an inspection system for identifying particularities, such as defects, in a structure. The inspection system includes a coordinated dual gantry system, a source inspection device, a detector inspection device and a gantry control system. The coordinated dual gantry system includes an exterior gantry that is configured to move externally to the structure and an interior gantry that is configured to move internally to the structure in synchronized motion with the exterior gantry. One of the inspection devices is mounted on the exterior gantry and the other inspection device is mounted on the interior gantry. The gantry control system maneuvers the detector inspection device and the source inspection device in synchronized motion with each other to each data, e.g., image, collection position on the structure, according to a programmed inspection sequence that controls movement of the inspection devices along the structure. In an embodiment, the gantry control system maneuvers the detector and source inspection devices while maintaining the relative alignment of the detector and the source at each data collection position. Together the inspection devices collect data, such as an image, from each data collection position on the structure.

[0023] In accordance with an aspect of the present invention, the inspection system includes an image acquisition system that controls image collection. In another embodiment, the inspection system includes a sensor or sensors which can accurately determine the location of the detector inspection device with respect to the structure just before data collection takes place. In an embodiment, the inspection system utilizes an alignment system such as, but not limited to, a target alignment system, a laser alignment system, a radio frequency alignment system, a physical alignment system, or an optical alignment system. In an embodiment, the exterior gantry is a master system and the interior gantry is a slave system.

[0024] In an embodiment, artificial axes are utilized that allow an operator to move an inspection device in a coordinate system that continually updates in space with respect to the orientation of the inspection device, rather than requiring desired motion of the inspection device to be input with respect to gantry axes. In an embodiment, the artificial axes register to, or are otherwise correlated with, the coordinate system of the structure to be inspected, e.g., the aircraft coordinate system. In an embodiment, reverse kinematics are utilized to derive a set of interior gantry motions that will achieve a sequence of data collection positions for the source inspection device corresponding to a programmed sequence of data collection positions for the detector inspection device, while maintaining the relative alignment and synchronized motion of the inspection devices.

[0025] Other features and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate by way of example, the features of the present invention.

BRIEF DESCRIPTIONS OF THE DRAWINGS

[0026] FIG. 1 illustrates a perspective view of an embodiment of an inspection system for inspecting an aircraft fuselage;

[0027] FIG. 2 illustrates an operational flow diagram of an embodiment of an inspection sequence for inspecting a structure;

[0028] FIG. 3 illustrates an operational flow diagram of an implementation of an inspection sequence for inspecting a structure; and

[0029] FIG. 4 illustrates an operational flow diagram of another embodiment of an inspection sequence for inspecting a structure.

DETAILED DESCRIPTION OF THE DRAWINGS

[0030] In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art, that the present invention may be practiced without these specific details. In other instances, well-known structures, devices and methods are shown in block diagram form and/or described more generally, in order to avoid unnecessarily obscuring the present invention.

[0031] An embodiment inspection system and method, constructed in accordance with the present invention, pro-

vides an efficient inspection system and technique for locating and identifying particularities, such as defects, in a structure. In an embodiment system and methodology of the present invention, the structure being inspected is an aircraft (e.g., fuselage and/or wings). In other embodiments the inspection system and method are used to examine other structures, including by way of example only, and not by way of limitation, fuel tanks and other pressure vessels. An embodiment inspection system and method reduces the time and cost required to prepare a structure, such as an aircraft, for inspection when compared to current visual inspection techniques. An embodiment inspection system and method also reduces the time to perform an inspection and increases the effectiveness and quality of the inspection.

[0032] Although the method and system of inspection may be used with a variety of structures to be inspected, for ease of discussion herein, the method and system will be described with respect to the inspection of an aircraft. Additionally, although the method and system of the present invention is not limited to use of x-ray inspection via image collection at various inspection points, and can encompass other inspection methods via, more generally, data collection at various inspection points, for ease of discussion, the method and system will be described herein with respect to x-ray inspection.

[0033] Referring now to the drawings, wherein like reference numerals denote like or corresponding parts throughout the drawings and, more particularly to FIG. 1, there is shown an embodiment inspection system 10. In an embodiment, the inspection system 10 of the present invention is utilized to inspect aging aircraft for defects, including by way of example only, and not by way of limitation, cracks and corrosion. In this embodiment, a first gantry 20 with an x-ray detector inspection device 40 is placed in a known position located outside of the aircraft fuselage 60, and a second gantry 30 with an x-ray source inspection device 50 is placed inside of the aircraft fuselage 60. The relative positions of the detector inspection device 40 and source inspection device 50 are then initialized. The detector inspection device 40 and source inspection device 50 are moved in a coordinated manner to each image collection position, such that the relative alignment of the detector inspection device 40 and source inspection device 50 is maintained.

[0034] In an embodiment, a programmed inspection sequence 70 directs image collection positioning for automated coverage of the fuselage 60. In an alternative embodiment, manual positioning is utilized. In an embodiment system 10 of the present invention, the detector inspection device 40 is placed on the exterior gantry 20, and the source inspection device 50 is placed on the interior gantry 30 for improved image quality. In an alternative embodiment, a reverse arrangement of the location of the x-ray source inspection device 50 and x-ray detector inspection device 40 is utilized. In alternative embodiments, non-destructive inspection techniques other than x-rays are used, such as ultrasound, thermography, and eddy current.

[0035] An x-ray inspection system 10, in accordance with the present invention, provides many desirable functions. Specifically, the inspection system 10 is capable of rapidly and accurately positioning an x-ray source inspection device 50 and a detector inspection device 40 in and around an

aircraft (or other structure) to be inspected. The inspection system 10 is capable of rapid assembly and disassembly, as well as registering the system's position with respect to the aircraft. The inspection system 10 is capable of executing an inspection sequence 70 with respect to the aircraft and exporting aircraft-based coordinates during the process. Further, the inspection system 10 produces, on command, smooth motions of the source inspection device 50 and the detector inspection device 40 to prescribed positions, such that the source inspection device 50 and the detector inspection device 40 are coaxial along the source beam at a known distance during the image capture process. In an embodiment, the inspection system 10 includes software and tools for creating and reviewing motion programs. In an embodiment, the inspection system 10 of the present invention includes standard computer interfaces for communication control and status reporting, as well as safety provisions for preventing injury to personnel or damage to the structure under examination.

[0036] Inspection System Components

[0037] An embodiment inspection system 10 of the present invention utilizes several different pieces of equipment, including an exterior gantry 20, an interior gantry 30, an x-ray detector inspection device 40 and an x-ray source inspection device 50. Additionally, position sensing equipment, alignment instruments and support equipment (e.g., electronics, power supply, and cabling), which are known in the art, are also utilized as needed. An embodiment of the x-ray inspection system 10 includes two independent, self-propelled gantry systems (the exterior gantry 20 and the interior gantry 30) which are controlled by a common gantry control system 74. In an embodiment, the exterior gantry 20 is a boom-type system, which houses the x-ray detector inspection device 40, and utilizes ground-based "rover" technology, as well as self-leveling jacks. In an embodiment, the interior gantry 30 is a track-based, boom-type system, which houses the x-ray source inspection device 50, and utilizes a conventional track system for longitudinal movement.

[0038] In an embodiment, the gantry control system 74 is contained in the exterior gantry 20, or is otherwise associated with the exterior gantry 20, and provides input and feedback capabilities for the operator 80, as well as a communication interface for exterior control, data sharing, and handshaking. An embodiment of the present invention further includes an image acquisition system 76 that coordinates image collection. In an embodiment, the image acquisition system 76 fully automates the image collection process once the x-ray inspection system components have been installed and aligned, and the inspection sequence 70 has been programmed (or reloaded from non-volatile memory storage) for controlling the movement of the inspection devices along the structure to be inspected. Further, the image acquisition system 76 may also record detector inspection device 40 and source inspection device 50 position data, as well as the corresponding image data produced by the detector inspection device 40 and source inspection device 50.

[0039] In an embodiment, the exterior gantry 20 consists of a mechanism with eight independent axes of motion (track-x, track-y, boom azimuth, boom elevation, boom telescopic, head pan, head tilt, and head roll). In an embodi-

ment inspection system, all axes of motion, except for head roll, are motorized and computer controlled. In an embodiment, a motorized vehicle, e.g., a rover, transports the exterior gantry 20 and includes locking features to fix the exterior gantry 20 firmly to the ground. This vehicle also provides a ninth axis of motion to the exterior gantry 20 along the axis of the fuselage 60 (z-axis).

[0040] In another aspect, a digital x-ray detector inspection device 40 is mounted to the end of the exterior gantry 20. In an embodiment, the x-ray detector inspection device 40 consists of a panel. In an alternative embodiment, the x-ray detector inspection device 40 consists of discrete detectors. Position-sensing equipment, such as interferometers, laser range finders, cameras, optical targets, or other surveying and/or aligning equipment may also be utilized as needed. An embodiment also includes support electronics, a computer, and a user input interface. In an embodiment, correlation, or registration, of the exterior gantry 20 to an airframe, or other structure to be inspected, is accomplished using self-leveling jacks, active electronics, and procedural registration techniques known in the art.

[0041] Referring to another component of the present invention, the interior gantry 30 consists of a mechanism with typically five independent axes of motion (track Z, boom azimuth, boom elevation, head pan, and head tilt). An x-ray source inspection device 50, such as a scanning or a conventional fixed source (depending on the x-ray system used), is mounted to the end of the interior gantry 30. In an embodiment, alignment instruments or targets are also utilized as required. Other support equipment, such as associated electronics, power supplies, and cabling are also implemented as required.

[0042] In an embodiment inspection system 10 of the present invention, registration of the interior gantry 30 to the airframe (or other structure being inspected) is accomplished through accurate engagement between the gantry tracks and the aircraft cabin seating tracks, combined with procedural registration techniques known in the art. In an embodiment, set up and calibration is designed to be simple, well-defined, and repeatable.

[0043] Artificial Axes

[0044] In accordance with the inspection system 10 of the present invention, each gantry is capable of movement along several independent axes. Generally, however, the operator 80 is interested primarily in the motion of the detector inspection device 40 (or the source inspection device 50) at the end of the gantry 20, and not the motion of the gantry 20 itself. The axes of motion in an inspection device based coordinate system, which is defined as the set of artificial axes, are mathematically related to the axes of motion of the gantries 20 and 30. Since the geometry of the gantry 20 and gantry 30 are well characterized, the gantry control system 74 can derive the associated motion of the gantry axes from the desired motion of the inspection device that an operator 80 inputs into a gantry user interface. The inspection device based coordinate system is designated herein as artificial axes. An embodiment gantry user interface allows an operator 80 to command and control the gantries 20 and 30, and the inspection devices 40 and 50. An embodiment gantry user interface includes a screen capable of displaying a graphical user interface ("GUI") and one or more user input devices, such as a keyboard, spaceball, mouse, trackball, etc.

[0045] In an embodiment, use of the artificial axes allows an operator 80 to move an inspection device in its coordinate system, thereby simplifying the operator's task of maintaining the inspection device in a constant orientation relative to the surface of the structure to be inspected, e.g., parallel or perpendicular to an aircraft fuselage, at all times as the inspection device is moved along the structure. Without artificial axes, the operator 80 would be required to characterize the desired motion of the inspection device with respect to gantry axes and manually manipulate several gantry axes at the same time while simultaneously attempting to follow the changing geometry of the structure to be inspected.

[0046] In addition, the artificial axes of the detector inspection device 40 can be registered to the control axes of a user input device, such as a spaceball. Then, if the operator 80 wants to move the inspection device 40 in a direction normal towards the surface of the structure to be inspected, a simple input is entered, e.g., pressing down on the spaceball. The gantry control system 74 software translates the simple artificial axes input, e.g., normal towards the surface of the structure, into a significantly more complicated and less intuitive motion along several combined gantry axes. Since the artificial axes follow the inspection device 40, i.e., the artificial axes are not fixed in space, the user's input is always intuitive.

[0047] The mathematics and data required for the artificial axes transformation are dependent only on the gantry and inspection device geometry, and do not require any inherent relationship to the object being inspected. However, the artificial axes can be explicitly aligned to the coordinate system of the structure to be inspected if so desired, as in the example above.

[0048] Inspection Method

[0049] Referring now to FIG. 2, one portion of an embodiment inspection method of the present invention is the programming of an inspection sequence 70. The inspection process can be accomplished either by automatically (as shown in FIG. 3) or by manually moving the detector inspection device 40 and source inspection device 50 to each desired data, e.g., image, collection position on the aircraft (or other structure to be inspected). Manual inspection sequencing does have some drawbacks. For example, there are a large number of identical aircraft that can be inspected in an identical manner, yet manual inspection sequencing cannot generally take advantage of this type of aircraft similarity. Additionally, large sections of an aircraft are very similar in configuration and can be inspected in an identical, or substantially similar, manner, yet manual inspection sequencing cannot generally take advantage of this type of repetition.

[0050] Further, an operator 80 must be fairly precise in moving the inspection devices 40 and 50 to the inspection positions on an aircraft. Since there can be on the order of three thousand different inspection positions on an aircraft, the manual process tends to be extremely slow and tedious. The extra time involved with manual inspection sequencing is a significant cost burden to the service that performs the inspection (or to the airline itself). Moreover, an operator 80 must take numerous precautions in order to be protected from the scattered x-ray radiation. Therefore, it is generally undesirable for an operator 80 to have to be involved in

tedious manual alignment of the inspection devices, while still having to maintain the necessary x-ray radiation precautions. For these and other reasons, it is advantageous to implement an automated inspection method in accordance with the present invention. However, in some embodiments of the present invention, manual inspection sequencing may still be utilized, for instance, if the geometry of the structure is unusual or difficult to program, if the motion control system has not been programmed with the geometry of the structure, for testing purposes, and so on.

[0051] As shown in FIG. 2, the first task in the automated process is to program the inspection sequence 70 into the gantry control system 74 for scanning the aircraft or other structure to be inspected. In an embodiment, this operation of programming the inspection sequence 70 is performed prior to any x-ray inspection. The inspection sequence 70 is created initially using only the exterior gantry 20 and some device simulating the geometry of the detector inspection device, which shall be called here the simulated detector. The detector inspection device 40 itself is not needed for this task, nor is the interior gantry 30. As described herein, "programming" refers to the process of defining a set of data points that constitute an inspection sequence 70 to be executed during image collection. The programming of the inspection sequence 70 of the present invention is usually only performed once per type of structure to be inspected, since subsequent structures of the same configuration can be inspected using the saved inspection sequence data.

[0052] This type of programming is a multi-step process consisting of several stages. The following describes an embodiment method of programming the inspection sequence 70 of the exterior gantry 20, as shown in FIG. 2. In preparation for the programming of the inspection sequence 70, the exterior gantry 20 (which is a rover in this embodiment), is moved adjacent to the aircraft of the type to be inspected. As described in Step 110, the rover 20 is positioned so that it is aligned with the longitudinal access of the aircraft. In an embodiment, the rover 20 is fixed in place with jacks. In Step 112, the axes of the rover 20 are initialized via interior home signals, limit switches, or the like. In Step 114 three or more reference points are then placed, or otherwise identified, on known fuselage 60 locations. In Step 116, the location and orientation of the simulated detector relative to the aircraft is then determined via triangulation to the reference points, using the surveying equipment located on, or otherwise associated with, the rover 20. In an embodiment, the surveying equipment is permanently mounted to the rover 20 in a known location.

[0053] Thereafter, the programming of the inspection sequence 70 for the exterior gantry 20 is commenced. In an embodiment, this process is assisted by the use of the artificial axes, as described above. The operator 80 uses the artificial axes to move the simulated detector in its coordinate system, thereby simplifying the operator's task of maintaining the simulated detector in an appropriate orientation, for instance normal to the aircraft, at all times as the simulated detector is moved along the aircraft. In Step 118 the operator 80 determines the position of an appropriate inspection sequence home location for the simulated detector. The home location for the simulated detector 40 is usually at an opening in the fuselage 60 through which the source inspection device and the detector inspection device

can communicate, through physical or visual contact. This home location position is then recorded in an image acquisition system 76 in Step 118.

[0054] In Step 120, the simulated detector located on the exterior gantry 20 is then moved to desired image collection positions outside the airframe (or other structure to be inspected), where the simulated detector is then oriented. In an embodiment, the simulated detector is positioned with a user interface device that allows the operator 80 to control the input with up to six degrees of freedom.

[0055] Optionally, the operator 80 may specify the type of scan point(s) for the desired image collection points, e.g., web, lap joint, framers, or the like. Through techniques such as visual inspection, or use of programmed instructions to analyze schematics or other relevant structural design information, the position of the desired scan points can then be determined.

[0056] In an alternative embodiment, the operator 80 can move the simulated detector continuously without stopping while the image acquisition system continuously collects structure surface data from sensors mounted to the exterior gantry. Another embodiment employs operator 80 input parameters of known airframe characteristics. Through manual determinations, or more automated processes, the position of the image collection points can then be determined.

[0057] In Step 122, the gantry control system 74 records these image collection positions.

[0058] In Step 124, the inspection sequence 70 for the detector inspection device 40 on the exterior gantry 20 is calculated through the image collection positions that were recorded. In an embodiment, this is an automated process that can, if desired, interpolate a new set of image collection positions from the geometry derived from the original set of image collection positions.

[0059] Previewing of the exterior portion of the inspection sequence 70 is then performed in Step 126, and any necessary adjustments can be made. This process proceeds relatively quickly because the inspection method does not require stopping at each image acquisition position during previewing. This inspection sequence 70 for the exterior gantry 20 positions can subsequently be used again in its entirety, or with modifications, on all x-ray inspections of aircraft of similar type.

[0060] In an embodiment inspection method of the present invention, the efficiency of the inspection sequence 70 programming process for the exterior gantry 20 can be increased by using the following techniques. Specifically, many sections of the inspection sequence 70, which represent portions of the fuselage 60, can be copied to other sections of the inspection sequence 70, which represent other similar portions of the fuselage 60. For example, the inspection sequence 70 for one entire half of the fuselage 60, e.g., cut down the longitudinal access, can be mirrored for the other half of the fuselage 60. Also, since a fuselage is composed of geometrically similar arcs, the inspection sequence 70 data for an arc can be utilized at several sites along the fuselage 60. Further, the programming method does not require actual image locations to be recorded. Instead, the operator 80 can record a set of locations from which a generalized surface geometry of the aircraft can be

deduced. The actual image collection locations can be interpolated using that geometry.

[0061] Another aspect of the inspection sequence 70 programming process, shown in Step 128, is the calculation of an inspection sequence 70 for the x-ray source inspection device 50 that is attached to the interior gantry 30. In an embodiment, this is an automated process referred to as "reverse kinematics" that, based on the inspection sequence 70 for the detector inspection device 40 and exterior gantry 20, generates a set of interior gantry motions that provides a synchronized inspection sequence 70 for the source inspection device 50 and interior gantry 30. In an embodiment inspection method of the present invention this process is implemented in the following manner. An offset is applied to determine the position of the source inspection device 50 relative to the detector inspection device 40 at each image collection position in the inspection sequence 70. An offset is a predefined distance between the source inspection device 50 and detector inspection device 40, which accounts for the thickness of the fuselage 60 or other intervening structure(s). Then, reverse kinematics is utilized to create the interior gantry 30 motions required to move the source inspection device 50 to its desired positions.

[0062] In an alternate embodiment inspection method of the present invention, other techniques for generating an inspection sequence 70 are utilized. In an embodiment, the aircraft surfaces are recorded using three-dimensional, visual-surveying instrument, e.g., optical or laser based. The inspection sequence 70 is then generated using this surface data. In other embodiments, blue prints or CAD data are used to generate a surface model of an aircraft from which an inspection sequence 70 is generated.

[0063] In another aspect of an embodiment inspection method, as shown in Step 130 of FIG. 2, the interior portion of the inspection sequence 70 is previewed and adjustments are made as necessary. During this procedure, both the detector inspection device 40 (or simulated detector) with attached exterior gantry 20, and the source inspection device 50 (or simulated source) with attached interior gantry 30, move through the inspection sequence 70 synchronously and smoothly. The process proceeds relatively quickly since the inspection sequence 70 does not need to stop at each image acquisition point during this procedure. In an embodiment, during the actual image collection inspection sequence 70, the detector inspection device 40 and source inspection device 50 stop at each image collection position for an x-ray image to be acquired, before moving on to the next image collection position, in a stop motion type of format. Additionally, arbitrary image acquisition points are selectable during test inspection sequences.

[0064] In Step 132 the inspection sequence 70 is approved and saved to the image acquisition system 76.

[0065] Referring now to FIG. 3, the next stage of the inspection method of the present invention involves the actual performance of the x-ray inspection. Initially, in Step 140 of this process, the exterior gantry 20 (e.g., rover) is moved into a position adjacent to the fuselage 60 and registered to, or otherwise aligned and/or coordinated with, the fuselage 60. In Step 142 the interior gantry 30 is assembled and aligned to the seat tracks located inside of the fuselage 60. Next, in Step 144 both gantries move into their pre-defined home positions. In an embodiment, in Step 146,

the interior gantry 30 and source inspection device 50 are accurately aligned to the exterior gantry 20 and detector inspection device 40 using visual systems, including by way of example only, and not by way of limitation, collimation, triangulation, or other optical alignment techniques. In another embodiment, physical alignment techniques are utilized, where the inner gantry 30 contacts a registration alignment point on the exterior gantry 20 in order to initialize alignment of the detector inspection device 40 and the source inspection device 50. In another embodiment, the interior gantry 30 can visually or physically be aligned to points or targets with known locations on the interior of the aircraft.

[0066] Before image acquisition commences, the operator 80 moves to a remote location where the operator 80 is protected from the x-rays.

[0067] In an embodiment, during image acquisition, a typical sequence of events proceeds in the following manner. As shown in Step 148 of FIG. 3, the image acquisition system 76 signals the gantry control system 74 to start the cycle. In Step 150 the detector inspection device 40 with attached exterior gantry 20 and the source inspection device 50 with attached interior gantry 30 move to the first image acquisition point. In an embodiment, in Step 152 the exterior gantry 20 extends a detector touch ring to make contact with the aircraft surface, to verify the image collection position of the inspection panel with respect to the aircraft surface. In an alternative embodiment, other sensors can determine the normal, i.e., perpendicular, distance from the detector inspection device 40 to the structure. Next in Step 154, the gantry control system 74 signals the image acquisition system 76 that it is in position. In response, in Step 156, the image acquisition system 76 requests position information from the gantry control system 74. In Step 158, the gantry control system 74 then sends actual position data of the detector inspection device 40 and the source inspection device 50 to the image acquisition system 76. As shown in Step 160, the image acquisition system 76 then collects and stores image data with the associated position data. As long as there are additional image collection positions, in Step 164 the image acquisition system 76 signals the gantry control system 74 that it is ready for the next position.

[0068] When the inspection sequence 70 is complete, the gantry control system 74 signals the image acquisition system 76 that the cycle is complete, and returns to a ready condition. However, if the inspection sequence 70 is not complete but there is a required pause in the sequence (e.g., the exterior gantry 20 has to move to the other side of the aircraft wing), the gantry control system 74 signals the image acquisition system 76 to wait. Once repositioned and aligned, the gantry control system 74 signals the image acquisition system 76 to resume. The detector inspection device 40 and exterior gantry 20 and the source inspection device 50 and interior gantry 30 then move to the next image acquisition point in Step 166. This process is repeated until there are no additional image collection positions and, in Step 168, image collection is complete.

[0069] In an embodiment, the exterior gantry 20 and interior gantry 30 are limited in motion along the longitudinal axis (z-axis) of the aircraft. In this embodiment, the exterior gantry 20 and interior gantry 30 are indexed in the direction of the z-axis in discrete intervals, e.g., every 12-15

feet. In other embodiments of the present invention, the gantries have either no limitations in motion or different degrees of limitations in motion along the longitudinal axis of the aircraft. In an embodiment, after the gantries are moved to new locations, they are recalibrated to previously surveyed points so that alignment is maintained.

[0070] In another embodiment, a digital x-ray image is obtained at each image collection position. These images are exported and examined in real time by the operator 80 at a remote position, or, alternatively, the images can be stored for later review.

[0071] In an alternative embodiment, both a first gantry, for a detector inspection device 40, and a second gantry, for a source inspection device 50, are located outside the structure to be inspected, such as an aircraft, for inspecting components of the structure, including, for example, the aircraft wing. In an example of this alternative embodiment, both the first gantry and the second gantry are located outside of an aircraft, in relative positions to allow the detector inspection device 40 and source inspection device 50 to be advantageously aligned along data collection points on the aircraft wing. In this alternative embodiment, both the first gantry and the second gantry may utilize ground-based rover technology.

[0072] Exemplary System Features

[0073] The performance requirements of both the exterior gantry 20 and the interior gantry 30 are such that relatively low power actuators may be used. In an embodiment stepper motors are used as the actuators. Even without collision detection capability, the use of these actuators minimizes the risk of damage due to interference from a fixed object, because the actuator, by its nature or by design, will stall. Conversely, a typical servomotor will apply full power when encountering an obstacle. In an embodiment, an inspection system 10 of the present invention includes intelligent fault sensing and response for each axis of motion, to ensure that loss of signal will result in smooth gantry stops. An embodiment also uses absolute encoder feedback on all axes, which provides absolute axis position information in the event of a stall, power outage, or other problem.

[0074] In one exemplary embodiment of the present invention, the system components of the inspection system 10 include the following non-limiting characteristics. The exterior gantry 20 incorporates a rover consisting of a four-wheel ground vehicle onto which a telescopic column mounts. The rover unit employs a four-wheel drive, four-wheel steering approach for ground maneuvering. In an embodiment, two of the wheels (for instance the front wheels) are mounted to a pivoting beam which aids in ground handling. Further, an onboard battery, which is intended for removing the rover from its shipping container or trailer, is also capable of providing backup power to the system for a short time. An automated jack leveling and stabilizing system is also used in the inspection sequence 70 process. The rover also includes hard rubber, or urethane, wheels. In an embodiment, the central processing unit of the gantry control system 74, the user input device, and any other input devices, are located and stored on the rover.

[0075] In an embodiment, the telescopic column of the exterior gantry 20 is a multi-staged, electrically-driven column that is used to position the boom to the proper working

height. An adjustable counterbalance cylinder carries the full load, so that the drive motor does not have to bear the full weight of the column. Further, a hydraulic fail-safe valve locks the counterbalance cylinder in the event of a power loss, preventing the column from descending. In an embodiment inspection system 10 constructed in accordance with the present invention, a trunion and swing drive reside atop the column and manipulate the telescopic boom arm in azimuth and elevation. Stepper motors drive these axes, and utilize wear compensation. Advantageously, the trunion and drive swing are easily removable from the column via hoisting.

[0076] In another embodiment aspect of the inspection system 10, the boom arm is a multi-stage, telescopic apparatus with a mechanically linked dynamic counterbalance. Additionally, the exterior gantry 20 provides the movement of pan, tilt and portrait, as well as landscape (roll) manipulation to the detector inspection device 40. In an embodiment, the detector gantry also includes a touch ring and actuator or other position-sensing detectors.

[0077] The interior gantry 30 of an embodiment inspection system 10 houses the x-ray source inspection device 50 and includes a track with a double rail design that is lightweight and easily assembled. In an embodiment, the track lays flat on the cabin floor of the interior of the aircraft and disperses load evenly to meet aircraft loading requirements. In an embodiment, the track uses a rack system for linear drive engagement. In an alternative embodiment, the interior gantry 30 uses, although not necessarily includes, a track system.

[0078] The interior gantry 30 further includes a trunion with a swing drive that resides atop the column and manipulates the boom arm in azimuth and elevation. In an embodiment, both axes are driven by stepper motors which include wear compensation. Further, the trunion and swing drive are configured to be easily removable from the column. The boom arm of the interior gantry 30 is a simple fixed length structure with a mass counterbalance. The boom arm provides pan and tilt manipulation for the source inspection device 50, as well as providing a source collision sensor.

[0079] Alternative, One Inspection Device, Embodiments

[0080] In an alternative embodiment, one inspection device, positioned either internally, externally, or internally and then externally, or vice versa, is used to collect data from various data collection points on the structure to be inspected. As with other embodiments, as shown in FIG. 4, with a one inspection device embodiment, the inspection sequence is first programmed into the gantry control system in Step 200. In an embodiment, programming can be accomplished by moving a gantry that will hold the inspection device and a simulated inspection device adjacent to the structure to be inspected first to a home position, and then to each desired data collection position. Alternatively, the programming can be accomplished by using schematics or other relevant structural data for the structure to be inspected, and selecting a pattern to be used for inspection, e.g., every six inch block comprising the structural surface, or specific data collection points, or specific features of the structure to be inspected, e.g., lap joints, framers, etc. An inspection sequence is then calculated via the data collection points that were recorded, or otherwise determined.

[0081] In an embodiment, in Step 202 a preview of the inspection sequence can then be performed, and any adjust-

ments to the sequence can be made. The inspection sequence is thereafter approved and saved in Step 204. The actual inspection performance can then be made, with the gantry and inspection device moving to each data collection point, in Step 206, and, in Step 208, collecting structural data for either real-time, or post data collection, review. This process is repeated until, in Step 210, there are no more data collection points. The review can be made either by an operator, or by an automated process using pre-defined criteria for reviewing the actual inspection data against.

[0082] The various system embodiments and methodologies described above are provided by way of illustration only and should not be construed to limit the invention. Those skilled in the art will readily recognize various modifications and changes may be made to the present invention without departing from the true spirit and scope of the present invention. Accordingly, it is not intended that the invention be limited, except as by the appended claims.

What is claimed is:

1. An inspection method for identifying particularities of a structure, the method comprising:

positioning a first inspection device inside of the structure and positioning a second inspection device outside of the structure, wherein one of the first or second inspection devices comprises a detector inspection device and the other of the first or second inspection devices comprises a source inspection device;

collecting data of at least a portion of the structure located between the first and second inspection devices;

moving the first inspection device on the inside and the second inspection device on the outside of a subsequent portion of the structure while approximately maintaining a pre-determined distance between the inspection devices; and

collecting data at the subsequent portion of the structure located between the inspection devices.

2. The inspection method of claim 1, wherein the first and second inspection devices are automatically moved to the subsequent portion of the structure according to a programmed inspection sequence that controls movement of the first and second inspection devices along the structure.

3. The inspection method of claim 2, wherein the method of producing the programmed inspection sequence that controls movement of the first and second inspection devices along the structure comprises an operator commanding the second inspection device to move through data collection positions and programming the data collection positions into the programmed inspection sequence.

4. The inspection method of claim 3, wherein the structure includes substantially similar portions, and wherein during programming of the data collection positions, data collection positions for the substantially similar portions of the structure are repeated within the inspection sequence during programming.

5. The inspection method of claim 2, wherein the method of producing the programmed inspection sequence that controls movement of the first and second inspection devices along the structure comprises an operator commanding a simulated inspection device to move through data collection positions on the structure and programming the data collection positions into the programmed inspection sequence.

6. The inspection method of claim 2, wherein the programmed inspection sequence that controls movement of the first and second inspection devices along the structure is produced from surface data of the structure generated from visual surveying equipment.

7. The inspection method of claim 2, wherein the programmed inspection sequence that controls movement of the first and second inspection devices along the structure is produced from surface model data of the structure derived from CAD data.

8. The inspection method of claim 1, wherein the source inspection device and the detector inspection device are manually moved to each portion of the structure to be imaged.

9. The inspection method of claim 1, wherein the source inspection device comprises an X-ray source and the detector inspection device comprises an X-ray detector.

10. The inspection method of claim 1, wherein the source inspection device is mounted on a first gantry and the detector inspection device is mounted on a second gantry, and wherein the first and second gantries are synchronized to move in coordinated motion with each other.

11. The inspection method of claim 10, wherein the first gantry and the second gantry each comprise one or more low power actuators.

12. The inspection method of claim 1, wherein one of the first or second gantries utilizes a track assembly, and the other of the first or second gantries utilizes a rover vehicle.

13. The inspection method of claim 1, wherein the first and second inspection devices are each initialized at home positions that provide for visual contact between the first and second inspection devices.

14. The inspection method of claim 1, wherein the structure comprises an aircraft.

15. The inspection method of claim 1, wherein the particularities that the inspection method identifies comprise cracks and corrosion.

16. An inspection method for identifying particularities in a structure, the method comprising:

placing a first gantry comprising an attached first inspection device in a position located outside of the structure;

placing a second gantry comprising an attached second inspection device inside of the structure;

initializing the relative positions of the first and second inspection devices;

moving the first and second inspection devices in a coordinated manner to each of a set of data collection positions according to a programmed inspection sequence that controls movement of the first and second inspection devices along the structure; and

collecting data of the structure at each data collection position.

17. The inspection method of claim 16, wherein the first and second gantries have axes, and wherein artificial axes are utilized that allow an operator to command the first inspection device to move in its coordinate system, rather than requiring desired motion of the first inspection device to be coordinated with respect to the first gantry axes.

18. The inspection method of claim 17, wherein the artificial axes register to an aircraft coordinate system.

- 19.** The inspection method of claim 16, wherein reverse kinematics are utilized to derive a set of second gantry motions that achieve a sequence of data collection positions for the second inspection device corresponding to a programmed sequence of data collection positions for the first inspection device.
- 20.** The inspection method of claim 16, wherein data collection is performed when the first and second gantries are intermittently stopped.
- 21.** The inspection method of claim 16, wherein the structure includes substantially similar portions, and wherein during programming of the data collection positions, data collection positions for the substantially similar portions of the structure are repeated within the programmed sequence of data collection positions.
- 22.** The inspection method of claim 16, wherein one of the first or second gantries utilizes a track assembly, and the other of the first or second gantries utilizes a rover vehicle.
- 23.** The inspection method of claim 16, wherein the structure comprises an aircraft.
- 24.** A method for creating an inspection sequence to use in the inspection of a structure, the method comprising:
- aligning an exterior gantry having an inspection device with the structure by initializing all the axes of the exterior gantry;
 - determining at least three reference points at locations on the structure;
 - determining the location and orientation of the inspection device on the exterior gantry relative to the structure via triangulation to the reference points;
 - determining one or more data collection positions for the inspection device on the exterior gantry;
 - positioning the inspection device on the exterior gantry in an orientation to the structure at a data collection position;
 - recording the data collection position of the inspection device on the exterior gantry;
 - using reverse kinematics to derive interior gantry axes motions to achieve a data collection position for an inspection device on an interior gantry corresponding to a data collection position of the inspection device on the exterior gantry; and
 - recording the corresponding data collection position for the inspection device on the interior gantry.
- 25.** The method of claim 24, wherein the inspection sequence automatically moves the inspection device on the exterior gantry to a data collection position on the structure.
- 26.** The method of claim 24, wherein the inspection device on the exterior gantry comprises an x-ray detector and the inspection device on the interior gantry comprises an x-ray source.
- 27.** The method of claim 24, wherein the exterior and interior gantries have axes, and wherein artificial axes are utilized that allow an operator to move the inspection device on the interior gantry in its coordinate system, rather than requiring desired motion of the inspection device on the interior gantry to be coordinated with respect to interior gantry axes.
- 28.** The method of claim 27, wherein the artificial axes register to an aircraft coordinate system.
- 29.** The method of claim 24, wherein the exterior gantry is a master system and the interior gantry is a slave system.
- 30.** The method of claim 24, wherein the interior gantry utilizes a track assembly and the exterior gantry utilizes a rover vehicle.
- 31.** The method of claim 24, wherein the inspection device on the exterior gantry and the inspection device on the interior gantry are each initialized at home positions that provide for visual contact between the inspection devices.
- 32.** The method of claim 24, wherein the structure comprises an aircraft.
- 33.** The method of claim 24, wherein the particularities that the inspection sequence is designed to identify comprise cracks and corrosion.
- 34.** An inspection method for identifying defects in a structure, the method comprising:
- moving an exterior rover gantry having a x-ray detector inspection device to a pre-determined position outside the structure and registering the exterior rover gantry to the structure;
 - mounting an interior rail gantry having an x-ray source inspection device onto alignment tracks at a pre-determined position inside the structure;
 - aligning the x-ray detector inspection device on the exterior rover gantry with the x-ray source inspection device on the interior rail gantry;
 - implementing a programmed inspection sequence to automatically move the detector inspection device and the source inspection device to each of a set of image collection positions; and
 - obtaining an x-ray image at each image collection position with the detector inspection device and the source inspection device.
- 35.** The method of claim 34, wherein the inspection method utilizes an alignment system for aligning the x-ray detector inspection device with the x-ray source inspection device, wherein the alignment system is selected from the group of: target alignment systems, laser alignment systems, radio frequency alignment systems, physical alignment systems, and optical alignment systems.
- 36.** The method of claim 34, wherein the exterior rover gantry is a master system and the interior rail gantry is a slave system.
- 37.** The method of claim 34, wherein the exterior rover gantry comprises axes and the interior rail gantry comprises axes, and wherein artificial axes are utilized that allow an operator to move each of the x-ray detector inspection device and the x-ray source inspection device in its respective coordinate system, rather than requiring desired motion of the x-ray detector inspection device to be input with respect to the exterior rover gantry axes and desired motion of the x-ray source inspection device to be input with respect to the interior rail gantry.
- 38.** The method of claim 35, wherein the artificial axes register to an aircraft coordinate system.
- 39.** The method of claim 34, wherein reverse kinematics are utilized to derive a set of interior rail gantry motions that achieve a sequence of image collection positions for the inspection device on the interior rail gantry corresponding to a programmed sequence of image collection positions for the inspection device on the exterior rover gantry.

40. The method of claim 34, wherein the obtaining of an x-ray image at each image collection position is performed when the exterior rover gantry and the interior rail gantry are intermittently stopped.

41. The method of claim 34, wherein the inspection sequence is programmed with the set of image collection positions, and wherein the structure includes substantially similar portions, and wherein during programming of the inspection sequence, image collection positions for the substantially similar portions of the structure are repeated within the inspection sequence during programming.

42. The method of claim 34, wherein the x-ray detector inspection device and the x-ray source inspection device are each initialized at home positions that allow for physical contact between the x-ray detector inspection device and the x-ray source inspection device.

43. The method of claim 34, wherein the structure comprises an aircraft.

44. The method of claim 34, wherein the defects that the inspection method identifies comprise cracks and corrosion.

45. A system for inspecting particularities in a structure, the system comprising:

- a dual gantry system, wherein an exterior gantry is configured to move externally to the structure and an interior gantry is configured to move internally to the structure;
- a first inspection device mounted on the exterior gantry;
- a second inspection device mounted on the interior gantry, wherein one of the first or second inspection devices comprises a detector inspection device and the other of the first or second inspection devices comprises a source inspection device; and
- a gantry control system that maneuvers the detector inspection device and the source inspection device in synchronized motion with each other to each of a set of data collection positions on the structure according to a programmed inspection sequence that controls movement of the detector and source inspection devices

along the structure, and wherein the detector and source inspection devices collect data at each of the set of data collection positions on the structure.

46. The system of claim 45, wherein the exterior gantry and the interior gantry each comprise one or more low power actuators.

47. The system of claim 45, further comprising a data acquisition system that controls the data collection at each of the set of data collection positions on the structure.

48. The system of claim 45, further comprising a detector touch actuator.

49. The system of claim 45, wherein the inspection system utilizes an alignment system from the group of: target alignment systems, laser alignment systems, radio frequency alignment systems, physical alignment systems, and optical alignment systems.

50. The system of claim 45, wherein the exterior gantry is a master system and the interior gantry is a slave system.

51. The system of claim 45, wherein the interior gantry comprises axes, and wherein artificial axes are utilized that allow an operator to command the second inspection device to move in its coordinate system, rather than requiring desired motion of the second inspection device to be commanded with respect to the interior gantry axes.

52. The system of claim 51, wherein the artificial axes register to an aircraft coordinate system.

53. The system of claim 45, wherein reverse kinematics are utilized to derive a set of interior gantry axes motions to effect a sequence of data collection positions for the second inspection device on the interior gantry corresponding to a programmed sequence of data collection positions for the first inspection device on the exterior gantry.

54. The system of claim 45, wherein the set of data collection positions comprise a set of image collection positions.

55. The system of claim 45, wherein the structure comprises an aircraft.

56. The system of claim 45, wherein the particularities that the inspection system identifies comprise cracks and corrosion.

* * * * *